lications of
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W LUCKIESH, D.Sc., D.E.
Lighting Research Laboratory
General Electric Co. Nela Park, Cleveland

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Applications of

GERMICIDAL ERYTHEMAL AND INFRARED ENERGY

By MATTHEW LUCKIESH, D.Sc., D.E.
Director, Lighting Research Laboratory
Lamp Department of General Electric Co. Nela Park, Cleveland

Straight from Lighting Research Laboratory of the General Electric Company has come this great contribution to the practical use of radiant energy in human welfare. The significant present-day importance of these methods is even surpassed by the major applications which will eventually become wide-spread. These deal with the health of human beings through the killing of air-borne and water-borne bacteria by means of germicidal energy, and by the prevention of contamination of food and other products. Discussed at length are the production and characteristics of artificial sunlight, which offers such great benefits in working and living conditions of all civilized human beings. There are increasing applications of fluorescence through the use of ultra-violet energy (black light); and extensive potential uses of infrared energy in the home and in industry. Along with this great range of new developments, the author has also included light for illumination, and the radiant energy which does and can accompany it for the benefit of human beings and other living organisms.

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FROM the first page to the last this book reflects the broad and diversified research of the author and his colleagues in light, vision and seeing—and in various aspects of ultraviolet and infrared energy. These researches furnish the scientific foundation for building a rational technology for many major applications of radiant energy. They include the use of germicidal energy for disinfecting air, water, and other materials; the production of artificial sunlight for specific and general purposes, not only in special therapeutic applications, but also for specific and general use in lighting of the future; the use of infrared energy for many purposes, and the great field of dual purpose lighting, which includes radiant energy for health, as well as light for seeing.

OTHER BOOKS BY THE AUTHOR

LIGHT, VISION AND SEEING, 1944
READING AS A VISUAL TASK (WITH FRANK K. MOSS), 1942
TORCH OF CIVILIZATION, 1940
COLOR AND COLORS, 1938
THE SCIENCE OF SEEING (WITH FRANK K. MOSS), 1937
SEEING AND HUMAN WELFARE, 1934
SEEING—A PARTNERSHIP OF LIGHTING AND VISION (WITH FRANK K. MOSS), 1931
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PORTABLE LAMPS, 1924
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THE BOOK OF THE SKY, 1922, 1933
VISUAL ILLUSIONS, 1922
LIGHTING THE HOME, 1920
ARTIFICIAL LIGHT, 1920
THE LANGUAGE OF COLOR, 1918
THE LIGHTING ART, 1917
LIGHT AND SHADE AND THEIR APPLICATIONS, 1916
COLOR AND ITS APPLICATIONS, 1915, 1921

Applications of Germicidal, Erythemal and Infrared Energy

BY

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Foreword

Early in the present century a research laboratory came into being with the usual personnel but with a unique charter. Its only obligation was to obtain and publish new knowledge of various aspects of light and radiant energy. A progressive management of a growing private industry adopted this means of acknowledging its indebtedness to science which had made that industry possible. Obviously, a similar debt is owed by industries, professions, practices and individuals throughout civilization.

Into that atmosphere of scientific purpose and freedom the author entered when gas lighting was still pin-pricking darkness along a rambling front; but it was also engaged in a rear-guard action with the rising forces of electric lighting. Carbon filaments in glass bulbs were already glowing steadily among the flickering gas-flames and more brightly than the gas-mantles. Electric lamps with fragile metal filaments were appearing on the scene and harsh carbon-arcs were sputtering on the streets and in some large interiors.

The combined forces of these light-sources, and the preceding ones, against an overwhelming darkness had been so feeble for so long that darkness had become accepted as the formidable competitor of artificial light. This erroneous concept warped thought, misguided research, and stunted practice in the realms of artificial light and its potential services to civilized human beings. Such a concept naturally cast darkness in the major role of an enemy to be fought and obscured a great principle and objective. Inevitably an adequate concept evolved which recognized natural light and lighting as friendly, beneficent competi-

tors of artificial light and lighting. In a broader sense they are exemplary guides to be followed and simulated, or even surpassed if possible, with controllable light in a controllable artificial world.

The completion of an adequate concept came easily in due course. Natural light and lighting, and the radiant energy of various wavelengths in sunlight, have been powerful environmental factors throughout the evolution of life on earth. Abundant evidence on every hand is proof of their influences. Everyone familiar with only a meager portion of this evidence accepts the great principle of adaptation and environment; but it is surprising how generally intelligent human beings exempt themselves from the influences of the powerful outdoor environmental forces.

Man has come indoors and, considering his insignificance compared with all-powerful Nature, he has achieved wonders. As he looks outdoors from the comparative safety and comfort of his indoor world, his superficial independence of Nature perhaps aids his egoism in ignoring what he left outdoors when he came indoors. Yet he himself is a testimonial of many influences of outdoor environmental factors. In the course of eons of evolution his visual sense was molded by, and adapted to, natural light and brightness-levels outdoors. He was molded physically and physiologically by these and other forces. Through the doorways of vision he has been molded psychologically by the imprints of outdoor distributions of brightness and color.

These are mere glimpses of the extended concepts which challenged the author long ago. The sources of artificial light and radiant energy available at that time were meager equipment for challenging the sun. However, science and technology were at work and the advent of more

and better sources was reasonably assured by inevitable progress. In the meantime two main highways, and many byways, invited research. These two main courses were found to be more or less intermingled, but they were separable into two distinct outlooks. One was confined to the relationships of light, vision and seeing. The other encompassed the effects of ultraviolet, visible and infrared energy upon health and hygiene and, by extension, included various other uses not directly involving human beings.

The publications of the author and his colleagues provide a chronological record of their work along these two main courses, and into some of the byways. In the complex realms of light, vision and seeing, the names of P. W. Cobb, L. L. Holladay and F. K. Moss are familiar and those of A. A. Eastman and S. K. Guth are beginning to appear. A. H. Taylor, by his genius and industry in devising instruments and methods of measurement, has contributed much along both main courses. He and G. P. Kerr, through many years of measurements of spectral energy, color-temperature and erythemal effectiveness, have provided valuable basic records of what daylight and its components, sunlight and skylight, are throughout the day and year. The same measurements applied to artificial sources reveal their standing as challengers of the sun.

Tungsten-filament lamps provide short-wave infrared efficiently and have extensive applications as yet undeveloped. With the advent of a variety of mercury lamps, extensive possibilities of radiant energy in the service of human beings are becoming realities. Fluorescent lamps supply footcandles as "cool" as those outdoors and light of various color-temperatures. A component of erythemal energy can easily be added to this revolutionary light-source. Artificial sunlight is now available from a variety of sources. It can be supplied locally or over large areas so that human beings

indoors can receive whatever beneficence, known or unknown, natural sunlight bestows outdoors. Complete control of erythemal energy is now possible. Indoors there need be no paucity of this biologically-beneficial energy in winter nor too much in summer. Recently the germicidal efficiency of artificial sources has been greatly increased so that a relatively insignificant wattage far outstrips the best sunlight in killing micro-organisms.

In the field of germicidal energy and its applications, L. L. Holladay and A. H. Taylor have made many contributions in the past decade. G. P. Kerr, T. Knowles, F. C. Kautzky and T. J. Borsch are also involved in techniques and measurements. To all these colleagues the author is indebted for much of the data in this book which deals primarily with some major effects of radiant energy and with applications that are bound to be extensive. Grateful acknowledgments are also extended to H. E. Wachs for the original drawings and to T. Knowles for the photography.

MATTHEW LUCKIESH

March, 1946

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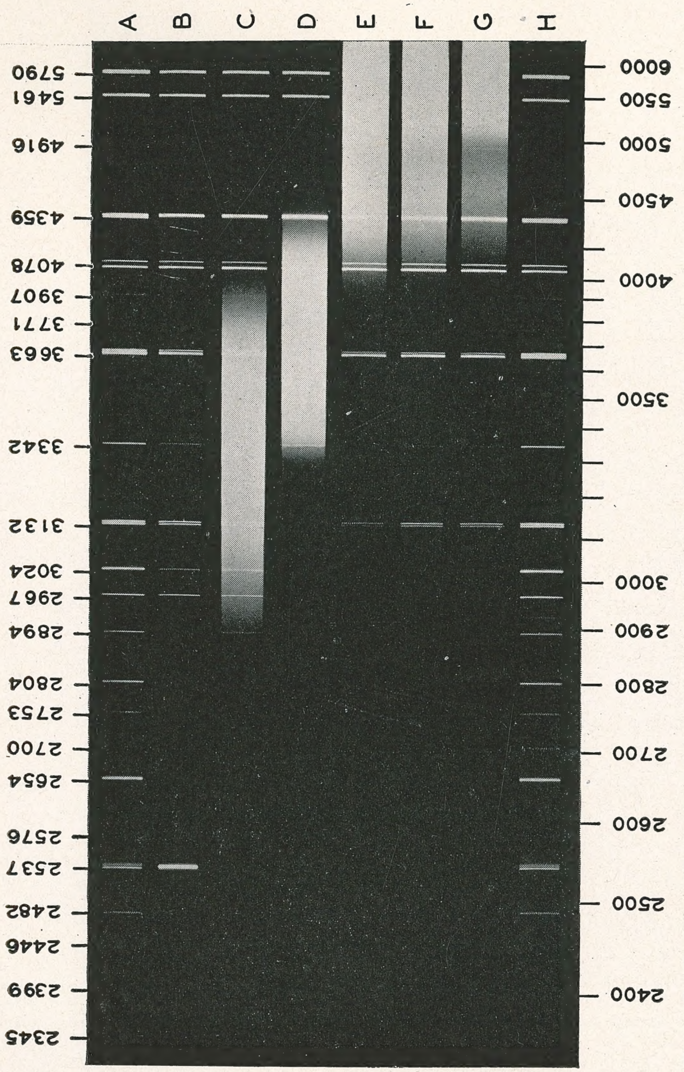


PLATE I. Spectrograms of visible and ultraviolet energy from various sources.

A. Quartz mercury-arc
B. 30-watt germicidal
C. Fluorescent sunlamp
D. Fluorescent 360 BL
E. Daylight fluorescent 6500° K.
F. White fluorescent 4500° K.
G. White fluorescent 3500° K.
H. Quartz mercury-arc

Challenging the Sun

NOTEWORTHY advances in the development of artificial sources of ultraviolet, visible and infrared radiant energy are actually challenging the sun. During the past decade modern science and technology have successfully challenged the sun in an increasing number of developments and applications. Civilized activities are no longer confined between sunrise and sunset. Efficient controllable artificial light is now as cool as daylight. Attainable intensities of illumination have greatly increased indoors. Infrared energy is finding new uses. Ultraviolet energy with its germicidal, biological, therapeutic, chemical and physical properties is now available from a variety of relatively new sources.

Ultraviolet energy in the spectral region beyond the short-wave limit of the solar spectrum is now available in intensities far exceeding those of the best tropical sunlight and skylight. Artificial sunlight is available for biological purposes exceeding the best sunlight in effectiveness. Whatever value there is in natural sunlight in various realms of health and disease, of erythema and tanning, of the production of Vitamin D, of testing of materials and of other known uses can now be matched, or more than matched, by artificial sources of radiant energy. It is likely that the unknown uses are even far more extensive than the known ones. New powerful tools are available for practicing in the realms of the known and for investigating in the realms of the unknown.

Our challenge to the sun is already formidable, but it is made with humility as well. Sunlight is beneficent. It is life-giving. Its eternal shower of blessings does not efface

or even dim the knowledge that among living things only the fit survive. Nature is ruthlessly destructive as well as eternally constructive. Knowledge, and the freedom and intelligence to apply it, are man's means of decreasing unfitness. They alone can provide some resistance, during a limited life-span, against the edict which inexorably takes its toll among unfit and unable living things. Having infinite time, Nature's efficiency springs from its inefficiency. However, man, working more narrowly toward his own welfare, can be more direct and efficient. We can bring the outdoors indoors for our own benefit and under our control. Thus we can even improve upon Nature in this direction as we have already in many other ways.

A POWERFUL ENVIRONMENTAL FACTOR

From the beginning of the simplest life on earth to the arrival of primitive human beings, an incomprehensible period of time elapsed. During all this time sunlight, both direct and scattered from the sky, was an environmental factor for countless species of living things in the long chain of evolution leading up toward human beings. It is unthinkable that radiant energy from the sun is not intricately woven into life-processes as other omnipresent environmental factors are, such as air and water. Human beings exhibit many superficial adaptations to their natural environment and many hidden ones have been revealed by scientific research. With such evidence before us it seems safe to assume that many other adaptations and needs have escaped detection as yet, owing to man's scanty knowledge of life and health processes.

Nearly two thousand years before modern science began in earnest, Aristotle thought that the fundamental elements of the cosmos were air, water, earth and fire. This was a natural conclusion for any thoughtful observer dominated by the egoism of a human being. But in unraveling the universe, egoism often misled, and still misleads to some extent, for human beings are prejudiced and relatively insignificant things among myriads of living organisms. However, in approaching the facts and mysteries of life and health of human beings, the relation radically changes, for human beings then become of primary importance. Now led by a justifiable egoism, one may well conclude that air, water, earth and sunlight are primordial elements of the natural environment which made outdoor human beings what they were, or are, physically, biologically and even psychologically. In one minute the need for air is as strikingly apparent as is the need for water in a week. Earth as the source of food becomes overwhelmingly important to those without food for a month. It is difficult to prove the direct need of sunlight and its radiant energy of various wavelengths, but this is not discouraging. Much evidence, both direct and indirect, already supports the philosophy of adaptation to this powerful environmental factor.

Sunlight varies widely in its intensity, duration and spectral composition according to location and season as well as from hour to hour. Plants live and die where they are born; therefore, various kinds have become adapted to the extensive variety of environments outdoors. They cannot survive radical changes in environment. Animals, free to range, have had to develop some degree of independence which apparently is achieved through a degree of storage capacity. If sunlight is essential to life-processes, human beings had to be protected in this manner from their own ignorance. Therefore, the benefits of sunlight are stored in food and possibly in the human body to tide human beings over the seasons and in their wanderings over the earth. At any rate, this can account for the fact that man-

kind has survived outdoor variations of sunlight, and particularly the unnatural indoor world. One of the most interesting and important questions confronting civilized human beings is the possible price they have paid by building an indoor world. Possibly some of the environmental factors which were left outdoors may account for the smallness of the net gain in health and longevity that civilized man has made, notwithstanding the enormous strides in development of obvious contributions in these directions.

A living thing may be considered to be a harmonious cooperation of processes, reactions and substances. Electrons, neutrons and protons form atoms and these form molecules. These in turn form protoplasm which is a constituent of the living cells of which human beings are constructed. Thus we complete in a few words a sketch of the chain of evolution whose actual history spans a period of uncounted millions of years. At the beginning of this chain from dead matter to living matter, the electrons and protons are intimately associated with radiant energy and, according to modern science, actually merge into it. The living cell is a unique transformer of energy which continually takes care of an influx of energy brought to it from without. Tracing life back toward its origin, rather simple conditions are met. From the earth come mineral salts; from the air come oxygen, nitrogen, and carbon dioxide; from the sun comes infrared, visible and ultraviolet radiant energy. Add water to these and life results. At every turn one meets radiant energy and, just as cosmogony teaches that the earth was born of the sun, so biology teaches that living things on earth owe their life and nourishment, directly or indirectly, to the radiant energy from the sun.

Modern medicine still trusts much to Nature and teaches that continued transgressions against Nature lead to

disease. But these same natural forces, obeyed and complemented or supplemented by science and invention, are potent in their ability to re-equilibrate a human being whose organization is out of harmony somewhere. And this discordance is very generally caused by ignorance, for the reason that so little is known of the human organism and the external influences. Human beings may well reflect upon the fact that for each living thing the universe may be divided into two parts. One is a relatively tiny part contained within the surface limits of the living thing. The other is the infinitely great part beyond. In considering the enormity of the disproportion between the two parts, it must be strikingly convincing that the organism is affected by the environment which he influences so little.

SUNLIGHT-THERAPY

Any retrospective view of the development of sunlight-therapy inevitably loses itself in the mists of primitive practices. Worship of the sun is almost universal acknowledgment of the beneficence of sunlight by primitive beings. Even in religious ceremonies of highest civilizations, symbolic uses of light are prominent. The most casual observation reveals the importance of light or visible radiant energy to plants. They grow toward the light and in darkness become mere ghosts of their true selves. Animals bask in the sun. Primitive beings expose their wounds to it, thus anticipating present post-surgical treatment with radiant energy by a long time. Sunlight has been killing germs for eons and still keeps the earth for human beings by doing so. Elementary sunlight-therapy has been practiced for centuries by various civilizations. Although instinctive recognition of sunlight as a remedy, preventive, adjuvant or tonic is not scientific proof of its powers, instinctive procedure persisted in by human beings for centuries often acquires

some weight. Its naturalness eventually gives it some authority which must be reckoned with. At least if we disapprove we should be able to disprove.

Egyptians treated the sick with sunlight. Hippocrates, who is honored as the father of medicine, erected a health temple to music, medicine and the sun. The Romans built solariums open to sunlight and Herodotus believed that sunlight was good for people who needed "restoration and the increase of their muscles." He even recognized the relative weakness of winter sunlight compared with summer sunlight. Many other civilized peoples in the sub-tropics practiced sunlight treatment. Eventually, as civilization spread northward in Europe, the practice of sunlight-therapy waned and even fell into disrepute. Quackery may have been the cause, for it flourishes in the twilight zone of knowledge.

Near the close of the eighteenth century, sunlight treatments revived and apparently with a scientific approach to the subject. About that time Faure advocated the treatment of chronic ulcers of the skin by means of sunlight. Later, when more scientific work verified some of his claims, others became seriously interested. In 1815 Chauvin published a treatise entitled *Insolation* in which he recommended the use of sunlight in all disorders with which feebleness, apathy and exhaustion were associated. The discovery of ultraviolet energy in 1800 may have given some impetus to sunlight-therapy, but nearly a century was to elapse before there was much scientific proof that ultraviolet energy near the short-wave limit of the solar spectrum was particularly effective in certain aspects of health and disease.

Toward the close of last century Finsen in Denmark and Rollier in Switzerland became everlastingly associated with actinotherapy and heliotherapy. They were responsible not only for a renewed interest in these agencies but also for a renewed confidence in them. Finsen demonstrated that lupus vulgaris is curable by ultraviolet energy. He contributed much in the development of therapeutic methods and techniques. In the same year that Finsen died, Rollier opened an institution in the Swiss Alps for scientific studies of heliotherapy. Apparently he had considerable success in the treatment of anemia, rickets, chronic ulcers and tuberculosis of skin, bones, joints and glands. He studied both the curative and the preventive value of radiant energy from the sun. His extensive work, following Finsen's re-introduction of sunlight into medical practice, inspired many scientific investigations and applications of the present century. Excellent treatises by outstanding authorities are now available, but many extravagant or unproved claims are also in circulation.

After Rollier, scientific applications greatly multiplied and physical science contributed new agencies. With Roentgen's discovery in 1895 of very penetrating rays which bear his name and the isolation of radium by the Curies in 1898, the present century was prepared for intense applications of these new sources of short-wave radiant energy in therapeutic practice. However, these rays are not components of sunlight and, therefore, are not discussed in the present work.

During recent years many new sources of ultraviolet, visible and infrared radiant energy have been developed. These, combined with methods of measurement, have added greatly to the possibilities of control of dosage and particularly to knowledge, for meaningful measurements provide the foundation of any science or practice. Notwithstanding these contributions, there are many uncertain regions and even gaps in the knowledge of the subject. Much of the uncertainty is directly traceable to meager knowledge

of physics on the part of those who use these physical agencies. The value of much of the published material is greatly reduced by the absence of accurate measurements and adequate identification of the spectral distribution of energy. Such deficiencies greatly depreciate the value of much biological and therapeutical research with radiant energy and applications of it. There is need for closer coordination of the knowledge of physical science with that of biology, medicine and therapy, in the various realms of education, research and practice. The author and his colleagues have made a specialty of developing measuring devices and techniques. The results provide a major reason for writing this book.

LIGHT AND RADIANT ENERGY

The term *light* is commonly used loosely, and chiefly in two senses. Sometimes it is confined to visual sensation as distinguished from radiant energy. This is a definite and logical usage. It is also commonly used to denote visible and invisible energy emitted by socalled light-sources or luminous radiators. This latter usage is indefinite and unnecessary inasmuch as terms such as ultraviolet, visible and infrared energy are already in use for this purpose and they are definite and accurate.

For the present purpose radiant energy may be defined as electromagnetic energy possessing only one inherent or fundamental characteristic—spectral character. Radiant energy cannot be discussed or understood effectively without dealing with its spectrum in terms of wavelengths or frequencies. Wavelength has been in use so long that it will be adhered to here, even though the use of frequency is increasing. Wavelength and frequency are directly related as reciprocals; that is, the frequency is proportional to the reciprocal of the wavelength. The converse is also true.

Now that radio receiving-sets and sending-sets are so common, it is easy to use them as analogies. Any source of radiant energy is a sending-station. It emits radiant energy of a definite spectral character, depending upon the composition and physical conditions of the radiating substance. The radiant energy will travel in straight lines until it is absorbed, reflected, refracted or diffracted by a medium or object.

In gases and vapors the atoms are usually free to emit the characteristic spectrum of the chemical elements involved. This is why the gaseous tubes and various arcs emit discontinuous or line spectra. The spectral lines are merely images of the linear slit of the spectroscope. In general, energy of shorter wavelengths is refracted or diffracted more by prisms or gratings, respectively, than energy of longer wavelengths. This provides a means of separating the heterogeneous radiant energy emitted by any radiator into energy of various wavelengths. In this manner accurate specification of spectral character becomes possible.

Any radiator which emits radiant energy is a sending-station and an atom of a given element under given conditions always broadcasts its own characteristic wavelengths. The eye, or more strictly the visual sense, is a receiving-set. It is only one of an uncounted myriad of receiving stations. Each receiving-set has its own characteristic selectivity as seen in other chapters, particularly Chapter III. The eye, for example, is selective or sensitive to the spectral range which naturally is described as the visible spectrum. The chief value of the foregoing picture is found not only in the analogy which is widely applicable, but also in the realization that the eye is merely one of a great many receiving-sets, each of which possesses its own peculiar spectral selectivity. Furthermore, one should not lose sight

of the fact that the eye cannot appraise invisible radiant energy for any of its manifold purposes.

Wavelength being a linear dimension or distance, its unit is easy to understand. Wavelengths of radiation are so short that very small units are necessary. In this discussion the Angstrom unit *A* is used. Is is equal to one ten-millionth of a millimeter, although it is seldom necessary to know its absolute value. The relationship of other wavelength units in common use is as follows:

$$10{,}000\ \text{A} = 1000\ \text{m}\mu = 1\mu = 0.001\ \text{mm.} = 0.0001\ \text{cm.}$$

Incidentally the foregoing wavelength is in the near infrared region not far beyond the long-wave limit of the visible spectrum which is at a wavelength near 7600 A. The Greek letter μ represents the micron and mμ the millimicron. The Greek letter lambda, λ, commonly indicates wavelength in scientific work. Therefore, it is convenient to use a logical abbreviation for expressing briefly a longer phrase. An expedient used extensively by the author for many years and with much satisfaction is, for example, $\lambda 2900$. In this case the numeral records the wavelength in Angstrom units and the simple expression, $\lambda 2900$, is a substitute for the words "wavelength of 2900 Angstrom units." The short-wave limit of the solar spectrum on a high mountain peak is near $\lambda 2900$.

Radiant energy has received many names, but with no consistency as to the method of choosing names. This adds greatly to the confusion. However, the entire matter is greatly simplified if one views the entire gamut of the wavelength-scale of radiant energy as representing the same *kind* of energy throughout, but differing only in wavelength. In addition, one should recognize that the names for the various regions commonly arise from the name of the explorer of that region, from the manner of production,

from their properties, or from their adjacency to other spectral regions. Therefore, names of spectral regions should not be taken too seriously and, of course, the limits or boundaries of the spectral ranges under each name should be considered only approximate. In fact, the limits of the

TABLE I

Approximate Wavelength Limits in Angstrom Units of Various Socalled Rays or Radiant Energy and Spectral Ranges Designated by Names in Common Use

	Wavelength Range
Gamma rays from radioactive substances	0–0.1
Roentgen or X-rays	0.01–500
Ultraviolet energy	0–3,900
Extreme or short-wave	0–2,000
Schumann region	1,000–2,000
Middle	2,000–3,000
Limit of solar spectrum	2,900–2,950
Near or long-wave	3,000–3,900
Visible energy	3,900–7,700
Violet	3,900–4,300
Blue	4,300–4,900
Green	4,900–5,500
Yellow	5,500–5,900
Orange	5,900–6,200
Red	6,200–7,700
Infrared energy	$7{,}700\text{–}10 \times 10^6$
Near or short-wave	7,700–14,000
Long-wave	$14{,}000\text{–}10 \times 10^6$

various spectral regions may actually overlap in some cases. For example, a high-voltage spark in a vacuum radiates energy of very short wavelengths which is known as ultraviolet, owing to the manner of production. On the other hand, these same wavelengths of energy are emitted by X-ray tubes under certain conditions and are then known as X-rays or Roentgen rays.

The approximate wavelength limits of various spectral regions of radiant energy are shown in Table I. All these rays or spectral components of radiant energy may produce heat when absorbed; therefore, the use of the term *heat rays*

for any specific portion of the spectrum, such as the infrared, is a misnomer and misleading. It is unnecessary to use this term in any sense. Such terms as *actinic rays*, *chemical rays* and *actinotherapy* are also indefinite and often misleading.

VARIOUS SPECTRAL REGIONS

It aids materially in understanding radiant energy as a physical tool and also its effects, to comment briefly upon various spectral regions. In Table I radiant energy beyond the infrared region has not been included for the reason that it is not present in sunlight or skylight. Beyond the region commonly known as infrared are socalled Hertzian and electric waves which are used in diathermy and wireless. Of still longer wavelengths is the radiant energy radiated from high-frequency and ordinary electric currents. Still others complete a long range of wavelengths. The longest known wavelength of radiant energy is greater than 12 kilometers or about 100 million million Angstrom units.[1] (See list of references following last chapter.)

Fig. 1 aids in visualizing the spectral region occupied by sunlight and also skylight which is scattered sunlight. The short-wave limit of the solar spectrum is in the neighborhood of $\lambda 2900$ to $\lambda 2950$ depending upon the altitude of the sun, the impurities in the atmosphere, and the altitude of the observer above sea-level. Solar energy of shorter wavelengths is absorbed by the upper atmosphere far above the heights attained by man.

It is also interesting to note the generalization indicated at the right-hand side of Fig. 1. Radiant energy of shorter wavelengths than that of sunlight is decreasingly penetrating as the wavelength decreases until the Roentgen region is reached. Then it is increasingly penetrating as the wave-

length decreases. This is also true of radiant energy at the other end of the spectrum. Of course, this is only a broad generalization, but it is interesting. An equally interesting

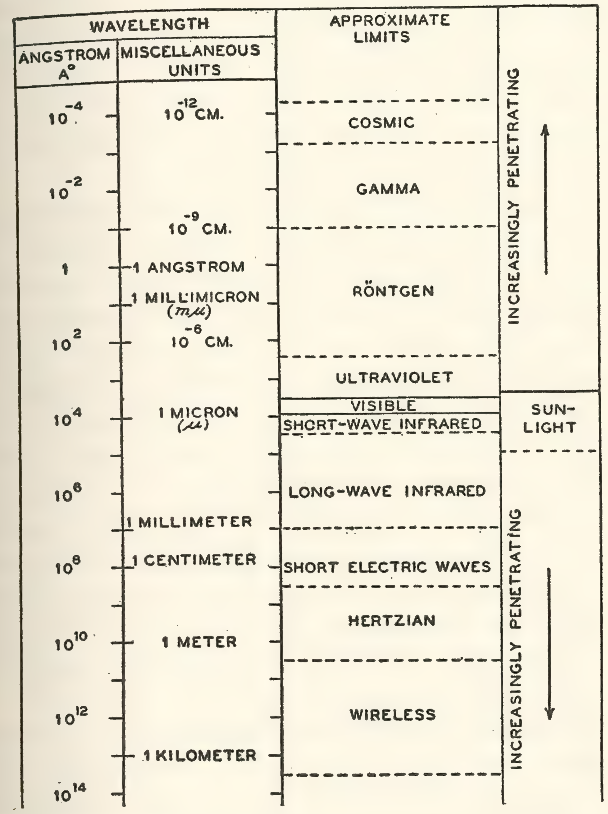


FIG. 1. The approximate wavelengths of the various spectral regions of the entire spectrum of radiant energy.

detail is the transparency of air and water to the radiant energy which our visual sense uses for seeing. These two substances are vital to human beings and their transparency to light and their colorlessness are of more than passing interest.

Cosmic rays have been known to exist for several decades. At the present time they are being studied intensely for clues to certain fundamental questions pertaining to the origin and constitution of matter. It is possible that they have some effect upon living matter. They are so penetrating that probably all, or nearly all, living cells on earth are reached by them. Until living matter is shielded from them and extensively studied, their effects in this respect will not be known.

Gamma rays (region of $\lambda 0.1$) are spontaneously emitted by radioactive elements, such as radium, or its breakdown products. They are valuable in the cure of certain diseases. They kill abnormal growths perhaps due to the less perfect organization of these compared with normal tissue. Certain descendants of radium emit alpha particles and beta particles (electrons) but these have the physical characteristics of radiant energy such as wavelength and frequency. *Cathode rays* are a misnomer for they are showers of high-speed electrons. These have been known for a long time, but their effects upon living matter and therapeutical uses have not been extensively studied. They produce fluorescence, ionization and photographic action. When they strike matter, such as the target in an X-ray tube, they generate Roentgen rays.

Positive rays are also a misnomer for they are showers of positive ions or protons, each of which has a much greater mass than an electron. They produce many of the same effects as cathode rays, but do not produce X-rays. They are produced in rather high vacua, as is true of socalled cathode rays. They move from the anode to the cathode; that is, in a direction opposite to that of cathode rays.

Roentgen rays ($\lambda 0.1$–$\lambda 5$) are produced by the bombardment of matter by cathode rays in a high vacuum. In their longest wavelengths they overlap the extreme explored region of ultraviolet energy. They produce fluorescence and photographic action and possess high penetrability, depending upon the density of the substance. In sufficient dosages they kill living cells.

Ultraviolet energy (shorter than $\lambda 3900$) first received its name because it was adjacent to or beyond the violet limit of the visible spectrum. From the viewpoint of biological and therapeutic effects this radiant energy has received much more attention than the visible and infrared energy. It produces fluorescence, photographic action and many known biological effects. It is convenient to divide it into three parts in reference to the visible spectrum, although certain important effects overlap these subdivisions.

Extreme ultraviolet energy (shorter than $\lambda 2000$) has found little use in therapy and biology because energy shorter than $\lambda 1850$ is absorbed by most substances, including air. In general, this is the least penetrating of all radiant energy. It must be produced and studied in a vacuum by means of special photographic plates, gelatine emulsions being opaque to it. Schumann studied the region from $\lambda 2000$ to $\lambda 1200$ and Lyman the region shorter than $\lambda 1200$. Millikan and others produced high-voltage sparks in vacua and obtained wavelengths well into the region already covered by X-rays. This is an example of radiant energy of certain wavelengths being known as ultraviolet or X-rays, depending upon the method of producing it.

Middle ultraviolet energy ($\lambda 2000$–$\lambda 3000$) is a very important spectral region from biological and therapeutic viewpoints. It is not transmitted by ordinary glass, but quartz is transparent throughout this range. Special glasses, particularly when free of iron, can be made to transmit various ranges shorter than $\lambda 3000$. The solar spectrum barely extends into this region for its short-wave limit is

near $\lambda 2900$. Nevertheless, solar energy between $\lambda 2900$ and $\lambda 3100$ is known to be very valuable in antirachitic and germicidal action, in the production of Vitamin D, in the production of erythema, and in extreme cases in the coagulation of egg albumen and the production of conjunctivitis. However, under ordinary conditions conjunctivitis is not caused by sunlight.

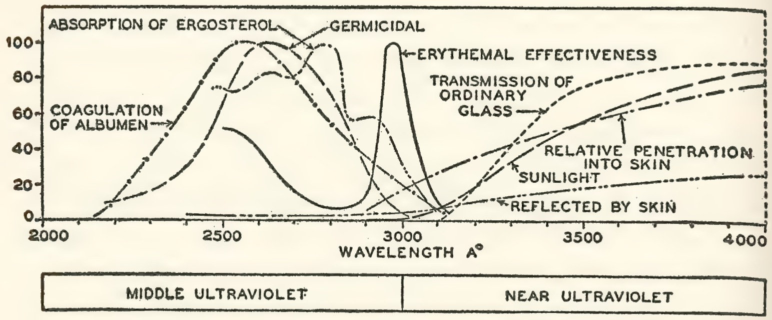


FIG. 2. Glimpses of important spectral data in the ultraviolet region from nearly the short-wave limit of transmission of quartz to the short-wave limit of the visible spectrum.

In Fig. 2 it is seen that some very important effects of ultraviolet energy are largely confined to this spectral region. The maximum of germicidal action is in the neighborhood of $\lambda 2600$, but the action extends definitely to $\lambda 3100$ and, if the radiation is intense enough, perhaps to $\lambda 3500$. The maximum for production of conjunctivitis and coagulation of egg albumen seems to be near $\lambda 2500$. This is also the neighborhood of one of the two maxima of erythemal effect, the more important one being near $\lambda 3000$. The production of Vitamin D by irradiating ergosterol is apparently due to energy somewhere between $\lambda 3100$ and $\lambda 2500$, although the wavelength of the most effective energy in this respect is not accurately known. Skin affections seem to respond to this radiant energy, but there is a strong

tendency to limit the spectrum for many other biological uses. Inasmuch as ultraviolet-therapy followed successes in sunlight-therapy and is still largely based upon the philosophy of sunlight as a natural factor, there is good reason for eliminating radiant energy shorter than $\lambda 2800$ and $\lambda 2900$ for general use and even for some specific uses.

Close inspection of Fig. 2 reveals the fact that the spectrum of sunlight barely extends into the middle ultraviolet region. It actually ends a little short of $\lambda 2900$. However, a number of major effects such as germicidal are produced maximally by ultraviolet energy of still shorter wavelengths. Therefore, artificial sources which emit abundant energy in the region from $\lambda 3000$ to $\lambda 2500$ and even to $\lambda 2200$ are powerful challengers of the sun for some purposes. In fact, the effectiveness of sunlight in killing germs, for example, is due to the enormous intensity of solar energy and the long exposures. The successful challenge of the sun by some new artificial sources of ultraviolet energy is adequately shown in later chapters.

Near ultraviolet energy ($\lambda 3000$–$\lambda 3900$) produces fluorescence very generally and causes photographic action. Ordinary glass is quite transparent between $\lambda 3900$ and $\lambda 3500$, but the transparency rapidly decreases until most glasses of ordinary thickness are fairly opaque at $\lambda 3100$. Special glasses are transparent throughout this region. Filters, practically opaque to visible radiant energy, are available for transmitting ultraviolet energy in this spectral range. These provide excellent means of utilizing fluorescent effects and even for producing erythema and other biological effects without appreciable visible radiant energy. Antirachitic, erythemal, germicidal, and tanning effects are chiefly confined to radiant energy shorter than $\lambda 3200$ although we have studied tanning of the skin for ultraviolet energy up to $\lambda 3700$. Most substances that are

transparent to visible radiant energy, including common glasses, become quite opaque somewhere in this ultraviolet region. Quartz, some special glasses, and pure water are important exceptions. It seems logical to expect that radiant energy of this spectral range, being quite abundant in sunlight, has many influences upon living matter which have not yet been revealed.

Visible energy (λ3900–λ7700) is the spectral range to which the visual sense of human beings is sensitive. This is not necessarily the range of sensitivity for eyes of all animals and insects. Chlorophyl requires visible radiant energy in order to play its part in vegetable life and growth. Thus this visible energy is all-important to plant life. Ultraviolet energy in sunlight seems to play no generally conspicuous part in the plant kingdom. Ultraviolet energy in the middle region is lethal in its effect upon plants. Hematin in the blood of animals may be more than a chemical analogy to chlorophyl. It may play an important part in utilizing radiant energy by human bodies.

The relative luminosity of radiant energy of various wavelengths to the human visual sense is shown in Fig. 3. The spectral range of visible energy is shown in relation to the ultraviolet and short-wave infrared regions. The spectral limits of the transmission of the media of the human eye are also indicated. Owing to the importance of water in bodily tissue and in the atmosphere, the spectral transmission curves of three thicknesses of water are shown along with the spectral energy curve for solar energy when the sun is directly overhead on an average clear day.

Human beings evolved under Nature's lighting, colors and brightness distribution outdoors. As mental beings they have not escaped vast and complex psychological influences. There is evidence of this on every hand. However, in therapeutic value these should generally be rated as of

secondary importance. Many therapeutic claims in this realm are extravagant or unsupported by knowledge. Unquestionably, when knowledge increases so enormously that psychological refinements can be added to therapeutic practice, they may be found to be important. Nevertheless,

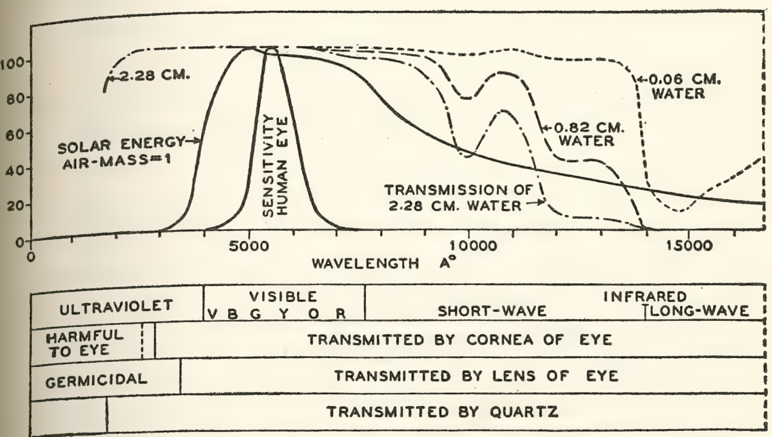


FIG. 3. The spectral range of radiant energy of most immediate importance to human welfare. To this may be added ultraviolet energy of maximal germicidal effectiveness beyond the solar spectrum.

before the biological effects are known and utilized, the psychological ones can scarcely assume primary importance excepting possibly in some purely mental disorders. The scanty knowledge which is available makes the field of socalled color-therapy a fruitful one for the practice of quackery.

Water is quite transparent to visible radiant energy as indicated in Fig. 3. Blood is transparent to λ6300–λ7700. Inasmuch as bodily tissue consists largely of water and is colored by blood, it is quite transparent to long-wave visible energy. Thus light can heat bodily tissue to a depth more comfortably than is done by direct contact of hot

towels. There is an extensive field of applications of long-wave visible and short-wave infrared for "light-baths" and local stimulation of circulatory processes.

Short-wave infrared energy (λ7700–λ14,000) penetrates deeply into bodily tissue as is indicated in Fig. 4. The radiant energy of maximum penetration is in the neighborhood of λ11,000. Therefore, the most efficient source for

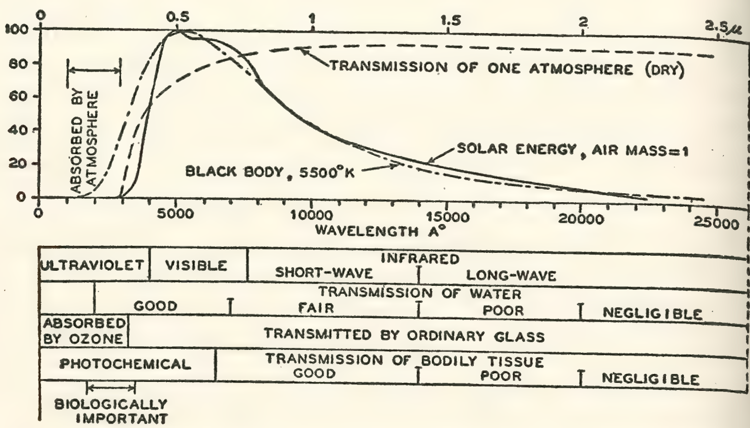


FIG. 4. The spectral range of radiant energy reaching the earth from the sun and in addition the spectral range of ultraviolet energy not transmitted by the atmosphere.

supplying radiant energy for heating bodily tissue at a depth is one which provides the greatest percentage of radiant energy in the neighborhood of λ11,000. This is not true of the sources commonly used for supplying infrared energy, which is too commonly designated as *heat rays*. The questions involved are rather simple ones in physics. Physical measurements show that bodily tissue is chiefly transparent to radiant energy between λ6000 and λ14,000 and maximally transparent at about λ11,000. Among all the practical sources available, ordinary tungsten-filament lamps of high wattage supply the energy of desired wave-

lengths most efficiently. Such lamps from 100 to 1500 watts are almost ideal sources of energy for heating bodily tissue at a depth. They are superior to carbon filament lamps so commonly used. The costly non-luminous or barely luminous radiators supplied for this purpose are relatively inefficient.

Therapeutic practices lag behind the physics of the subject and some of these are excellent examples of the lack of grasp of the fundamental knowledge available. Of course, a hot towel, a hot-water bag, or any kind of heater will heat the bodily tissue to a depth by inward *conduction* of heat from the heated surface but with more discomfort to the patient than when a source of penetrating radiant energy is used. The efficient and comfortable way is to heat at a depth by radiant energy transmitted to and absorbed by the deeper layers of bodily tissue. A bath cabinet in which eight 300-watt tungsten-filament lamps are used (one in each of the eight inside corners) is a good application of this principle. With a minimum of discomfort a maximum of heating effect at a depth is obtained. The results are liberal perspiration, cleansing of skin, stimulation of circulatory processes, and possible other benefits of bathing the body with radiant energy which, before the donning of clothes, was a primary factor in the outdoor environment.

Long-wave infrared energy (longer than λ14,000) possibly has unknown influences. Of course, it contributes toward heating the bodily tissue but not as efficiently or effectively as the short-wave infrared as is indicated in Fig. 4. This long-wave infrared energy can be controlled by absorbing glasses as indicated in a later chapter. Most glasses are fairly transparent to infrared radiant energy as far as λ28,000. Special apparatuses which produce electric waves and high-frequency energy, diathermic devices and

socalled artificial-fever machines are yielding promising results. Some of the effects are due to excessively high temperature which can be obtained quickly in the depths of bodily tissue. These can be very efficient devices for they produce radiant energy of very long wavelengths to which bodily tissue is quite transparent.

ARTIFICIAL SOURCES OF RADIANT ENERGY

In challenging the sun we are interested first in the spectral range of radiant energy from the sun and sky. This begins at about λ2900 in the ultraviolet region and extends through the visible region and far into the infrared region. However, our interest is not confined merely to this spectral range but extends into the variety of effects produced by solar energy. Many of these effects are far more efficiently produced by ultraviolet energy shorter than λ2900. Therefore, in the consideration of artificial sources of radiant energy we are concerned with a spectral range extending throughout the middle ultraviolet and to at least λ1800 where ultraviolet energy is absorbed by air and ozone is produced.

Quite a number of artificial sources are now available. A few have been available for many years, but during the past decade new sources have greatly extended the practical possibilities of successfully challenging and even outdoing the sun in many applications of radiant energy, particularly ultraviolet energy. Although these artificial sources are discussed in detail in later chapters, it may be helpful to describe them briefly at this point.

Carbon arcs have many uses and by impregnating the carbons with appropriate compounds considerable control over the spectral character of the emitted radiant energy can be exercised. The short-wave limit can be further controlled by glass envelopes of various kinds. In Fig. 5 is

shown the spectral distribution of energy emitted by two bare carbon arcs. (See Plate IV.)

Quartz mercury arcs of various wattages have been available for many years. They still have many uses, but as is true of carbon arcs, many old and new applications of radiant energy are better served by relatively new sources. Quartz mercury arcs as well as bare carbon arcs emit energy

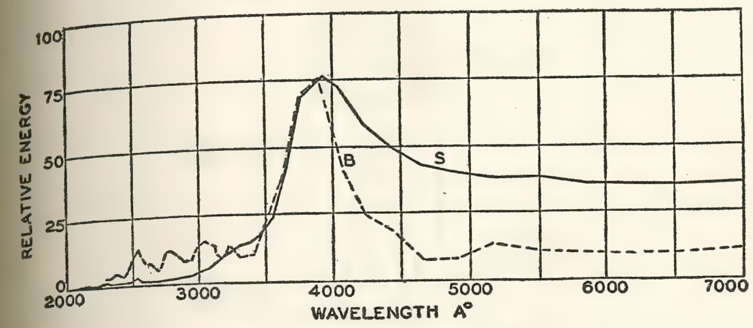


FIG. 5. Radiant energy of various wavelengths emitted by two types of carbon arc; *B*, therapeutic carbons; *S*, sunshine carbons.

throughout the middle ultraviolet region. The production of ozone generally indicates radiant energy shorter than λ2000.

Sunlamps are distinguished from ultraviolet generators by limiting the ultraviolet spectrum to approximately the spectral range of sunlight. Actually the short-wave limit of sunlamps is generally at about λ2800. This limit is readily accomplished by using a special glass.

The S-1 sunlamp, illustrated in Fig. 6, consists of a tungsten filament in parallel with a small mercury arc. With its essential transformer it is rated at 500 watts. It emits considerable light, actually about 7200 lumens initially, at a luminous efficiency of 18 lumens per watt. It also emits considerable infrared energy. Its spectral limit

in the ultraviolet region is about λ2800 which is determined by the special glass of the bulb. Inasmuch as a source of one spherical candlepower emits 4π lumens, the luminous intensity of this lamp is about 600 candles. (See Plate III.)

The S-4 sunlamp, illustrated in Fig. 7, consists primarily of a mercury arc in a small quartz tube. The enclos-

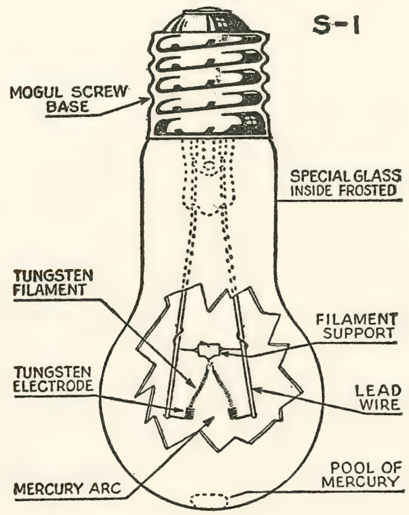


Fig. 6. A diagrammatic view of the important details of the Type S-1 lamp which, without its essential external ballast, is approximately a 400-watt sunlamp.

ing bulb consists of special glass. With its essential transformer it is rated at 123 watts. The RS-4 sunlamp is the same lamp in a reflector bulb coated inside with aluminum. Its overall rating is 123 watts. These lamps emit relatively less light, but are quite powerful sources of ultraviolet energy as far as λ2800, being comparable to the S-1 sunlamps which are about four times the wattage. Obviously the composition of the enclosing bulb determines the short-wave limit of the emitted ultraviolet energy.

The RS sunlamp, illustrated in Fig. 8, is similar to the S-4 but has a tungsten filament for ballast and a bimetallic starting switch within the aluminized reflector bulb. No auxiliary transformer is necessary. Therefore, it can be used in the usual sockets available for common filament lamps on ordinary lighting circuits. Its overall rating is

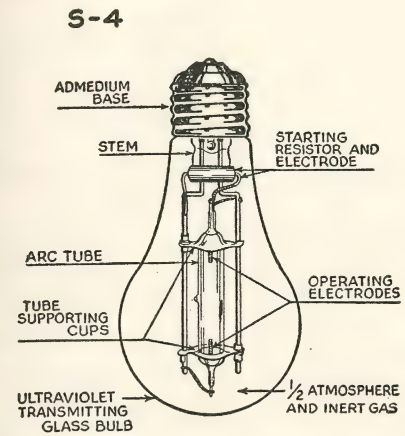


Fig. 7. A diagrammatic view of the important details of the Type S-4 lamp which, without its essential external ballast, is approximately a 100-watt sunlamp.

275 watts. The filament emits considerable light and infrared energy. The mercury arc of the RS sunlamp provides ultraviolet energy as far as λ2800. This limit is determined by the composition of the glass bulb.

The AH-6 lamp, illustrated in Fig. 9, is a high-pressure mercury arc in a small quartz tube. It emits 65,000 lumens at a luminous efficiency of 65 lumens per watt. As a light-source its luminous intensity is about 5000 candles. The quartz tube in which the mercury arc is confined is cooled by water flowing through an outer jacket of special glass. The spectral limit of the ultraviolet energy which is

emitted is determined by the transparent water-jacket and by additional filters. The BH-6 is the same lamp without the water-jacket, but cooled by jets of air impinging on the quartz tube containing the mercury. Its rating is 1000 watts when water-cooled and 900 watts when air-cooled.

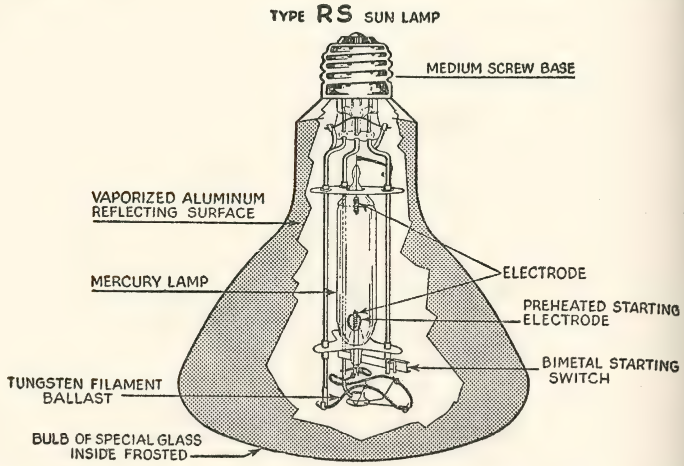


FIG. 8. A diagrammatic view of the important details of the Type RS lamp. This is approximately a 275-watt sunlamp which does not require an external ballast.

These lamps are powerful sources of ultraviolet and visible energy. With these lamps intensities of such energy can be obtained far in excess of the most intense tropical sunlight.

A number of other high-pressure mercury arcs of the H type are available primarily for lighting purposes. They also emit considerable energy in the near-ultraviolet. These vary in rating from 100 to 3000 watts with luminous efficiencies of 40 lumens per watt without taking the auxiliary ballast into account. They may be worth considering where abundant long-wave ultraviolet energy is desired

along with abundant light or visible energy. The AH-9 lamp is rated at 3000 watts with an output of 120,000 lumens. Its luminous intensity is about 10,000 candles. Obviously, the glass bulb determines the spectral limit of the ultraviolet energy which is made available.

A number of sources of ultraviolet energy in the near-ultraviolet region are now in use primarily for exciting

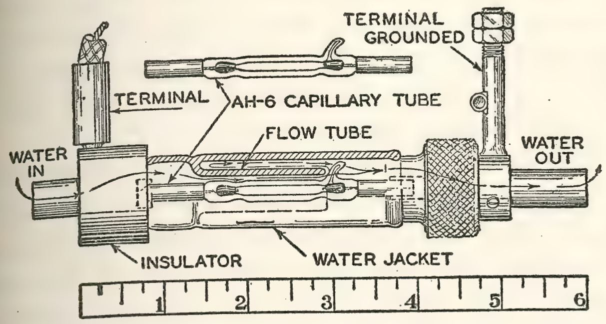


FIG. 9. A diagrammatic view of the powerful Type H-6 high-pressure water-cooled mercury-arc. The external jacket of quartz or special glass may be omitted and the capillary tube may be cooled by blasts of air. This is a 1000-watt lamp exclusive of the external ballast.

fluorescence. These are compact mercury arcs with bulbs or filters consisting of deep purplish glass which transmits ultraviolet energy efficiently but transmits relatively little light or visible energy. The term *black light* has become associated with these sources.

A mercury arc at very low pressure is an efficient source of ultraviolet energy, nearly all of which is emitted in the neighborhood of $\lambda 2537$. This energy is maximally germicidal. Therefore, when such sources are confined in bulbs or tubes of special glass highly transparent in the spectral region of $\lambda 2537$, they have become known as germicidal lamps. They are exceedingly powerful sources of germicidal energy. For example, a 30-watt germicidal lamp

is about as effective in killing germs as a 300-watt quartz mercury arc of the type which has been available for many years. Obviously, these new socalled germicidal lamps have many other applications besides killing bacteria and other living organisms. (See Table XIX.)

Tungsten-filament lamps are fairly efficient sources of light and are excellent sources of short-wave infrared energy which is abundant in sunlight. Such energy is finding many new uses. Equipped with a bulb of special glass, tungsten-filament lamps emit measurable amounts of erythemal or antirachitic ultraviolet energy. They are then known as CX lamps. (See Plate III.)

Fluorescent lamps are recent additions to the ranks of light-sources. They provide light which is as "cool" as daylight. They are essentially low-pressure mercury arcs. Great control over the spectral character of the emitted energy is possible by properly choosing and mixing the fluorescent materials (phosphors) with which the inner surface of the glass envelope is coated. The uses of these lamps are not confined to lighting. By means of special phosphors they become excellent sources of energy extending through the near-ultraviolet region and into the middle ultraviolet region. (See Plate I.)

All these sources have their place in challenging the sun. Their effectiveness is discussed in detail in various chapters. (See Plate XVI.)

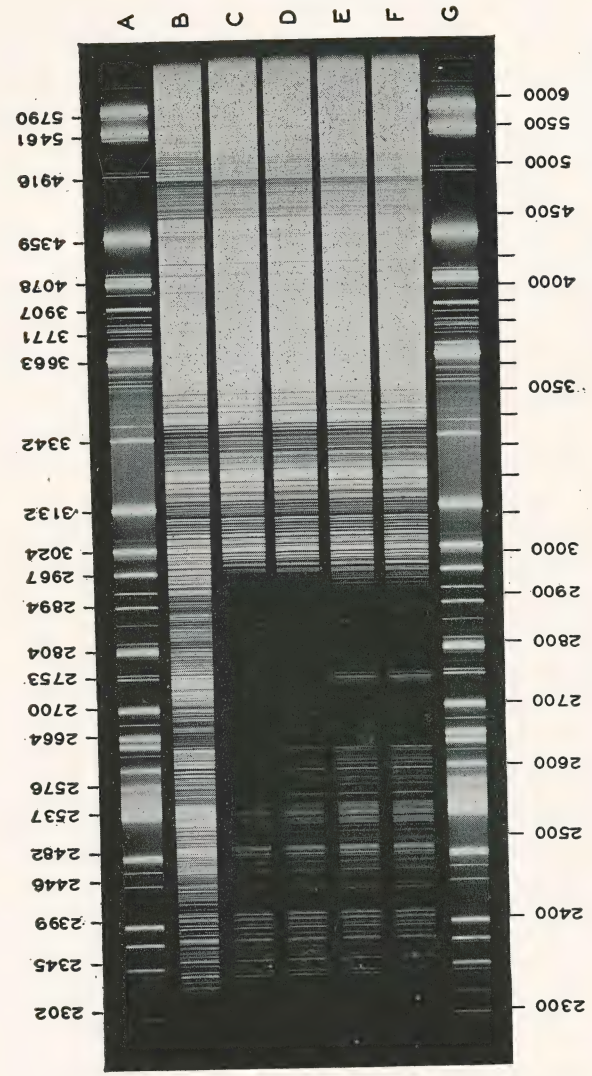


PLATE II. Showing the absorption band of ergosterol. A and G, quartz mercury-arc. B, iron arc. C, D, E, and F, iron arc through decreasing depths of ergosterol.

Sunlight and Skylight

IN THE world of living things outdoors, countless life-processes are at work. To a great degree they are the products of the outdoor environmental factors and influences which antedate man by an enormous period of time. Now they are important to us in many ways and probably in more ways than we can possibly comprehend. Only by a blinding prejudice of an inexcusable egoism can man ignore the overpowering influences of sunlight and skylight. Nature provides an enormous laboratory of life-processes and environments. It is inevitable that modern science is invading that laboratory from many directions and viewpoints. Observations and measurements are the bricks in the structure of knowledge. Proper coordinations of these are actually evolving the sciences and increasing the practices which spring from them.

Among our major questions as we survey Nature's laboratory is, What is sunlight? Another question equally important in many ways is, What is skylight? To answer these questions it is necessary to measure the radiant energy of various wavelengths and to ascertain, also by means of meaningful measurements, the effects of energy of various wavelengths and to discover unknown effects. In such fields as biological effectiveness of radiant energy, it is reasonable to assume that the unknown is still a far greater realm than the known. But enough is known both in detail and in generalization to warrant an ever-increasing interest in Nature's outdoor laboratory of life and energy. The knowledge gained from systematic observation and measurement of sunlight and skylight, and their effects upon

living and even lifeless things, is basically important in countless ways.

Certain variations in sunshine and in the appearance of the sky are obvious hourly, daily and seasonally. The daily variations are in part analogous to those due to latitude. However, there are factors such as ultraviolet and infrared energy which vary greatly and unobviously. The composition and mass of the atmosphere cause great variations. The effects of smoke and dust are sometimes obvious. The effect of water-vapor and the concentration of ozone are not obvious. A clear blue sky may appear the same on one day as another but the radiant energy from the same patch of blue sky on two different days may differ considerably. We see sunlight reflected from a cloud but we do not see the ultraviolet energy also reflected from the cloud just as efficiently as it is reflected from freshly fallen snow.

These obvious and unobvious variations complicate the problem of standardizing sunlight or skylight in terms of energy of different wavelengths. Further complications arise in weighting the radiant energy according to a given effect of that energy. This effect may be biological such as erythemal, antirachitic or tanning. It may be purely chemical or physical as in the case of non-living substances. The effects upon living cells and organisms are likely to be physical, chemical and biological, complexly combined. Some effects are delayed in the matter of time. They may be interesting as short-range or long-range effects. Thus the importance of sunlight ranges in interest from effects of the immediate present to those involved in bio-climatology and beyond.

It is not the purpose of this book to invade the many avenues of ultimate effects of sunlight, skylight and similar radiant energy from artificial sources which now challenge

the sun. From decades of research by the author and his colleagues, involving measurements of radiant energy and of some of its major effects, knowledge is available that is too generally overlooked and even absent in applications of radiant energy from the sun or similar energy from artificial sources in research and practice. Much of the published material involving the use and effect of radiant energy is at best only of qualitative value owing to the absence of meaningful quantitative measurements of energy, spectrally and otherwise. Laurens,[2] Duggar,[3] Mayer,[4] Ellis and Wells,[5] Spoehr,[6] Blum,[7] Huntington,[8] and others have published extensive treatises on effects of radiant energy. The present work aims to supply the basic foundation of measurements of radiant energy of various wavelengths and their effectiveness in certain major ways as already indicated in Fig. 2. Such a foundation of measurements, devices and techniques is of importance in an increasing variety of research and practice.

RADIANT ENERGY FROM THE SUN

The spectral range of energy from the sun at the earth's surface, if the atmosphere were not present, is illustrated by the upper curve in Fig. 10. The effect of atmospheric absorption is shown by the lower curve which is fairly representative of spectral energy measurements made at sea-level on a clear day with a moderate amount of water-vapor in the atmosphere. The vertical scale of values may be considered to be microwatts of energy (in each spectral band having a width of 100 Angstroms) on a horizontal surface of one square centimeter at noon provided the day is a very clear one. On many clear days in the temperate zone the energy values are considerably less than these. However, for the present the absolute values of energy are not important. The locations of the absorption

bands of water-vapor, carbon dioxide, oxygen and ozone are shown by the black areas.

It is fairly obvious from Fig. 10 that the amount of ultraviolet in solar energy is greatly affected by the absorption band of ozone. The short-wave limit of the ultraviolet

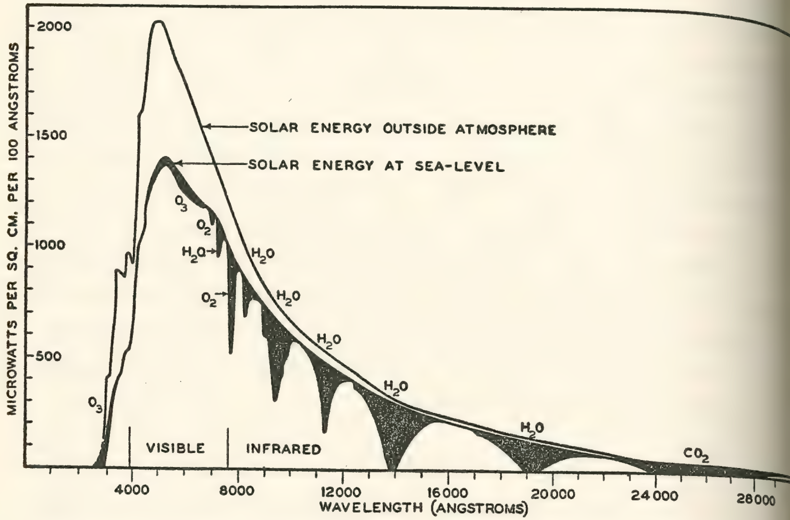


Fig. 10. The spectral distribution of radiant energy from the sun which reaches the earth's surface on a very clear day. The effects of atmospheric absorption in the various spectral regions are indicated approximately by the black areas.

is greatly affected by the concentration of ozone. This can only be illustrated convincingly by plotting the short-wave portion of the ultraviolet spectrum on a large scale. However, the energy outside the atmosphere is only of passing interest. We live near the bottom of this ocean of atmosphere.

Another obvious fact is the great absorption of infrared energy by water-vapor. It is commonly considered that the average amount of water-vapor in the atmosphere on

clear days is approximately equivalent to an inch of water in liquid state but this varies greatly over the earth. The absorption of infrared adds materially to the coolness of daylight as an illuminant. This aspect of light is considered in a later chapter dealing with common illuminants and the absorption of water which is illustrated in Fig. 3 is further discussed in the chapter dealing with infrared energy. Approximately one-half the total solar energy reaching the earth's surface at noon on a clear day in summer is in the visible spectrum.

To one who has spent decades in the fields of light, radiant energy, vision and seeing it becomes an obvious and striking fact that human eyes evolved to utilize sunlight very efficiently. It is seen in Fig. 10 that the visible spectrum, the region to which the human visual sense responds, is the dominant part of the solar spectrum. It is also the least affected by the atmospheric absorption bands shown. There are limits to the spectral range which a simple lens can utilize without excessive chromatic aberration. This and other details reveal that the visual sense of human beings is very well adapted to utilize the best spectral range of solar energy for seeing. It has seemed to the author that this is one of the most striking facts of evolution and adaptation to environment among the countless array of such facts. Considering its importance in many ways this striking fact has been relatively ignored.

The total solar energy reaching a given surface varies considerably with the amount of water-vapor in the atmosphere. Therefore, the intensity of solar energy varies greatly over the earth from arid to humid regions. Naturally this variation is further increased by the amount of air or the air-mass through which the solar energy must pass. This varies with the daily variations in the altitude of the sun

and with the variations due to geographic latitude. Fig. 10 hints at the fact, which has been verified by many measurements, that the intensity of visible and even ultraviolet energy at noon does not differ greatly in the temperate zone from that in the tropics. Contrary to common assumptions, the actual level of illumination at noon on a clear day in midsummer is not appreciably less at 40° latitude than at the equator. Even the erythemal effectiveness of solar energy does not differ markedly in the two cases, considering the variations even at a given locality.

According to Abbot, the maximum intensity of solar energy or radiant power at sea-level near Washington, D. C., varies from 75 to 95 watts per sq. ft. on a horizontal surface. Actually the watt is a unit of radiant power. The watt-hour is a unit of energy. At the top of Mt. Whitney, nearly three miles above sea-level, the intensity of solar energy or rate at which it falls on a horizontal surface was found by Abbot to be about 115 watts per sq. ft. In Cleveland, Ohio, the maximum intensity of solar energy on a horizontal surface on average clear days in midsummer was found by A. H. Taylor to be about 80 watts per sq. ft. Data for various spectral ranges are presented in Table II. Inasmuch as we shall deal considerably with microwatts per sq. cm., the data are also presented in terms of this unit of radiant power. One watt equals one million microwatts and one watt per sq. ft. equals 1076 microwatts per sq. cm. Inasmuch as various units are used to measure intensity of radiant energy and radiant power, the following approximate equivalents may be helpful.

1 milli-calorie per minute per sq. cm.
0.001 gram-calorie per minute per sq. cm.
0.07 milliwatt per sq. cm.
70 microwatts per sq. cm.
700 watts $\times 10^{-7}$ per sq. cm.
700 ergs per sq. cm. per sec.

TABLE II

The Maximum Intensity of Solar Energy or Radiant Power on a Horizontal Surface on Average Clear Midsummer Days at a Suburb of Cleveland, Ohio, Whose Latitude Is 41.5° N.

Spectral Range	*Watts per Sq. Ft.*	*Microwatts per Sq. Cm.*
Shorter than λ3,500	1.1	1,180
λ3,500 to λ4,000	2.2	2,360
λ4,000 to λ7,000	39.	42,000
Longer than λ7,000	38.	40,800
Total	80.3	86,340

Such a shower of radiant energy upon the earth's surface as indicated in Table II, if continued for one year, is sufficient to melt a layer of ice about 300 feet thick. An acre of ground will receive from spring until fall a total amount of solar energy equivalent to several hundred tons of coal. The heat value of the crops produced under this solar energy is equivalent to less than a ton of coal. Plants actually utilize only about one percent of the solar energy incident on their leaves.

SUNSHINE AND CLOUDINESS

Water-vapor in the atmosphere, by absorbing infrared energy, causes considerable variation in the amount of solar energy reaching the earth's surface. In a more obvious way, condensation into fogs, clouds, mists and rains causes still greater variations. A thick layer of clouds has much the same reflecting and transmitting characteristics as a few inches of freshly fallen snow. If the cloud layer is just thick enough to render the sun invisible to an observer on the earth's surface, much of the solar energy incident upon the cloud layer is reflected outward into space. The long-wave infrared is diffused less than the short-wave infrared and visible energy. However, as is obvious from the measurement of light, cloudiness causes enormous variations in the

solar energy reaching the earth. The amount of ultraviolet energy is reduced by cloudiness even more than light is.

In a country as large as the United States and with conspicuous mountain ranges, it is not surprising that the duration of sunshine and cloudiness varies greatly over the

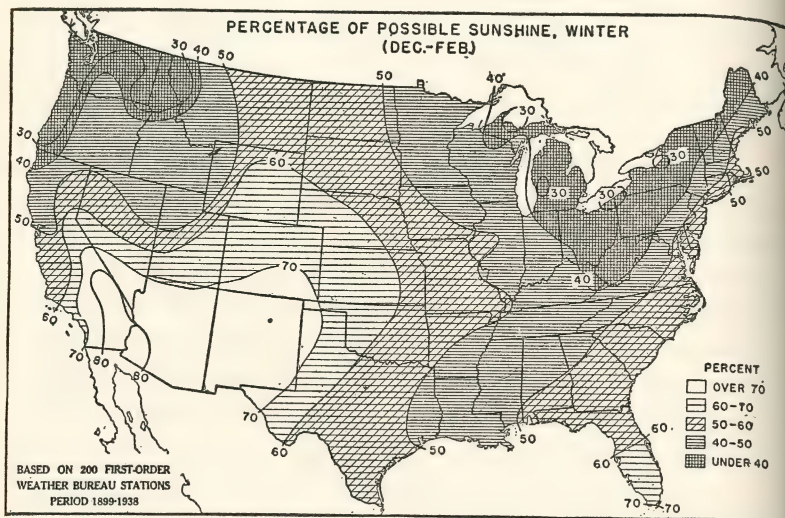


FIG. 11. Percentages of possible sunshine averaged over four decades by the U. S. Weather Bureau for December, January and February.

entire country. Actually, cloudiness of some areas in the northeast and northwest sections is as great as 70 percent of the total hours of sunshine that are possible in winter. In other words, in these sections, the actual hours of sunshine in winter are only 30 percent of the possible. This is illustrated in Fig. 11 which is based [9] on data obtained by 200 first-order Weather Bureau stations over a period of 40 years. Similar data for summer are presented in Fig. 12. Even during the three summer months there are very large areas over which cloudiness occupies 30 percent of the total possible hours of sunshine.

The maximum duration of possible sunshine varies with the latitude and the time of year. The possible duration of sunshine at the equator varies approximately from 11 to 12 hours daily during the entire year. At a latitude of 50° the possible duration of sunshine varies from about

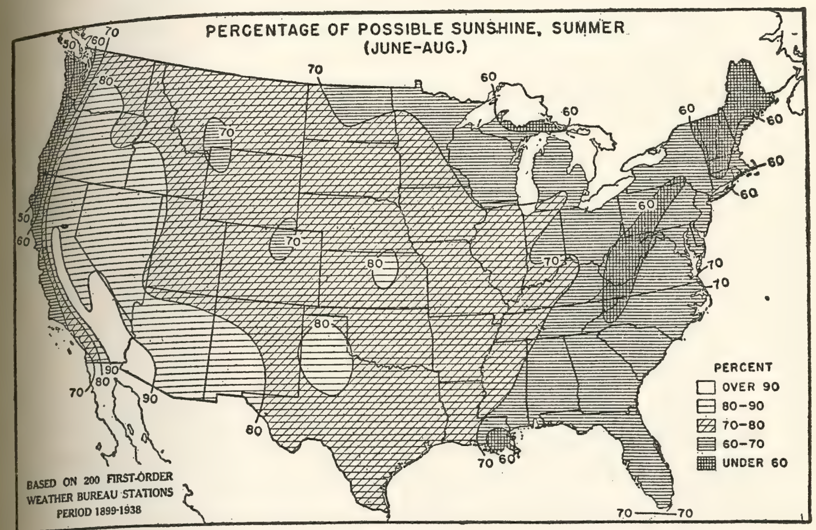


FIG. 12. Percentages of possible sunshine averaged over four decades by the U. S. Weather Bureau for June, July and August.

8 to 16 hours from midwinter to midsummer. At a latitude of 60°, the variation is from about 6 to 19 hours. In high latitudes the effect of the inherently lower altitude of the sun in summer is compensated to some degree by the long hours of possible sunshine. Some plants, for example, profit by the long day notwithstanding the short summer. In Table III is shown the maximum possible duration of sunshine [10] for various latitudes for the shortest and longest days in the year.

In Fig. 13 the seasonal effect upon the duration of possible sunshine is combined with cloudiness for the entire

year in the vicinity of Cleveland at 41.5° N. latitude. This illustration will apply to any locality of the same latitude by altering the boundary between sunshine and cloudiness to fit the records for that locality. By reducing the average cloudiness somewhat, Fig. 13 becomes approximately representative of the average for the entire country.

TABLE III

Maximum Possible Duration of Sunshine for the Shortest and Longest Days in the Year

Latitude	*December 22*		*June 21*	
0°	12 h	07 m	12 h	07 m
10°	11	32	12	43
20°	10	55	13	20
30°	10	13	14	05
40°	9	19	15	01
50°	8	04	16	23
60°	5	52	18	52
65°	3	34	22	03

From sunrise to sunset the altitude of the sun varies from zero degrees to a maximum and to zero degrees again. During this course solar energy passes through a maximum mass of atmosphere at sunrise to a minimum at noon and again to a maximum at sunset. The effect of solar altitude and atmospheric absorption is well illustrated in Fig. 14 by the variation of illumination measured in footcandles on a horizontal surface. However, the effect upon the infrared and ultraviolet energy reaching the earth is even still greater, as is evident later.

When the sun is overhead or nearly so, the solar energy passes through one atmosphere or one air-mass. At noon on December 21 at 40° N. latitude the solar energy must pass through atmosphere approximately equal to an air-mass of 2.4. During the early daylight hours on any day of the year the air-mass is much greater. Thus altitude of the sun has a profound effect upon the solar energy

reaching the earth and particularly upon the biologically-effective ultraviolet energy. The sky compensates for this to some degree as shown later.

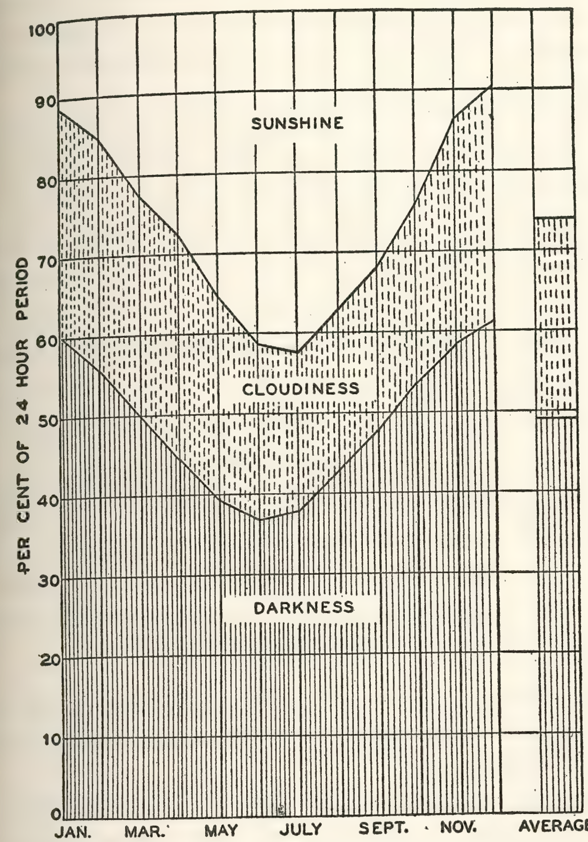


Fig. 13. The seasonal variation of sunshine, cloudiness and darkness in the vicinity of Cleveland at 41.5° N. latitude. By reducing the cloudiness somewhat, this is approximately representative of the average for the entire United States.

LIGHT AND LIGHTING OUTDOORS

At the bottom of the ocean of atmosphere human beings, and all living organisms and non-living matter, are in an environment determined in part by this great filter of atmosphere. If this filter of air suddenly became transparent

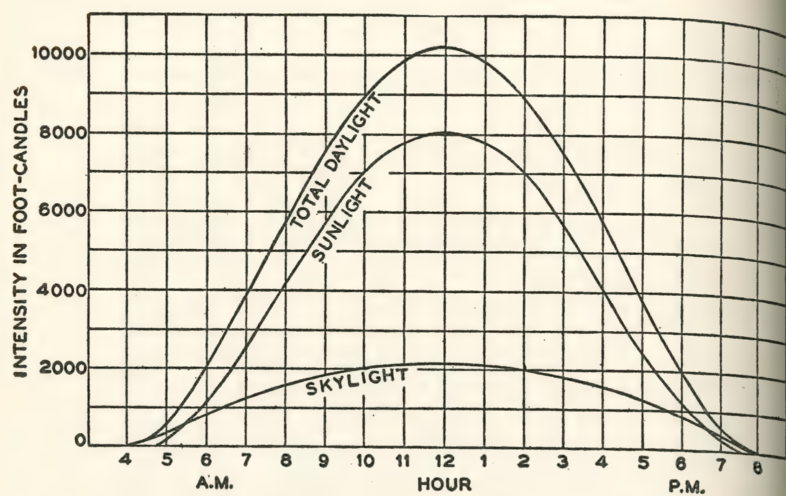


FIG. 14. The variation of sunlight and skylight measured in footcandles on a horizontal surface on clear days in midsummer.

to solar energy of all wavelengths, all living things would be destroyed by the short-wave ultraviolet energy to which they are not adapted.

Besides absorbing solar energy, particularly in the short-wave ultraviolet region, the atmosphere scatters some of the solar energy. It does this selectively; that is, it scatters energy of short wavelengths more than energy of longer wavelengths. This is evidenced by the blue sky. The molecules of gases are comparable in size with the wavelengths of solar energy. As a consequence short-wave infrared is scattered more than long-wave infrared. Ultraviolet energy

is scattered more than visible energy. Blue light is scattered more than yellow, orange, or red light. This accounts for the bluish color of the sky, for skylight is entirely scattered sunlight. The particles of condensed water-vapor are large in size compared with the wavelengths of solar energy. Therefore, fogs and clouds do not appreciably scatter sunlight selectively. Clouds do not appear bluish by transmitted light but are the color of the light illuminating them. That light is a combination of direct sunlight and the light from the sky above the clouds. The color of light from an overcast sky is that due to combined sunlight and skylight.

Without this scattering of solar energy there would be no skylight. In place of the blue sky of a clear day there would be a dark night sky in the daytime. Stars would be visible and the glare of the sun would be relentless in a black sky. Shadows would be harsh and dark in the daytime. They would be black unless receiving light reflected by other objects. There would be no dawn or dusk. The transition from day to night would be abrupt with no twilight interval.

The magnitude of this scattering of sunlight is illustrated in Fig. 14 for a clear day in midsummer. The effect of the sun's altitude is shown by the variation of light, measured in footcandles on a horizontal surface. On unusually clear days in temperate and tropical zones the intensity of illumination due to direct sunlight sometimes may be as great as 8000 footcandles on a horizontal surface when the sun is at the zenith. On such days the sky—scattered sunlight—contributes about 2000 footcandles or about 20 percent of the total light on a horizontal surface at noon. The contribution of skylight throughout the day varies much less than that of sunlight. The illumination on a horizontal surface due to sunlight and skylight rarely reaches a maximum of about 10,000 footcandles.

As we ascend in altitude, the skylight decreases and the sunlight increases. At an altitude of 23,000 feet above the earth on a cloudless day, the author found that sunlight was 96 percent of the total light on a horizontal plane. Even at that altitude much of the "sky" is already below the observer.

The intensity of ultraviolet energy increases somewhat with altitude but the short-wave limit of sunlight is not appreciably extended when the atmosphere is clear. Much of the effect of the absorption band of ozone apparently is still above the observer even at high altitudes. The ultraviolet energy from the sky is discussed later in this chapter.

Daylight as an environmental factor is also of interest from the viewpoint of vision and seeing. Footcandles are misleading in these respects. Brightness is what we see. Brightness also determines adaptation of the visual sense, its acuteness and its sensitivity to brightness differences. In general, the visual sense is most effective and seeing is easiest at the brightness-levels of common areas confronting us in the foreground and middle distances of landscapes. These are brightness-levels of between 100 and 500 footlamberts on a sunny day. A footlambert is the brightness produced by one footcandle on a perfectly diffusing and perfectly reflecting white surface which reflects all the light incident upon it. The ideal brightness-levels for seeing are apparently obtained by levels of illumination somewhere between 100 and 500 footcandles on a perfectly white surface or by 1000 to 5000 footcandles on a gray surface which diffusely reflects only 10 percent of the incident light. Daylight intensities and brightnesses outdoors in the daytime—even light itself—have been grossly ignored in the development of the science of vision. The more inclusive science of seeing has given them their proper importance.

The average level of illumination outdoors is far less than the maximum of 10,000 footcandles. Taking into account cloudiness and the changing altitude of the sun during the day and the year, the average level of illumination between dawn and dusk in the temperate zone is probably of the order of one-fourth the maximum. Some instances of localized lighting indoors by means of artificial light have already approached this average outdoors.

Artificial light-sources have successfully challenged the sun in some respects. Any quality or spectral character of daylight outdoors can be fairly well simulated by artificial light at the present time. Light from fluorescent lamps approximates the coolness of daylight. In other words, the radiant energy per footcandle is of the same order of magnitude. Nature's lighting, whether it be the *indirect lighting* from an overcast sky or a combination of direct sunlight and diffused skylight, can readily be duplicated in artificial lighting. Studied with discrimination, Nature provides a helpful textbook in the realms of light, color, lighting, vision and seeing. Human beings cannot escape the influences of Nature's light and lighting. They have left their permanent marks upon human beings, physically, physiologically and psychologically. Only an inexcusable egoism blinded by its inexcusably narrow prejudices can ignore Nature's powerful and omnipresent environmental factors.

ULTRAVIOLET COMPONENT OF SOLAR ENERGY

The obvious and unobvious variations in atmospheric absorption make it very difficult to standardize solar energy. The steep rise of the spectral energy near the short-wave limit of the solar spectrum makes it necessary to use a very narrow spectral band in energy measurements. Adding to these difficulties involved in making measurements, the fact

that the ultraviolet energy near the end of the solar spectrum is a fraction of a thousandth of the total solar energy,

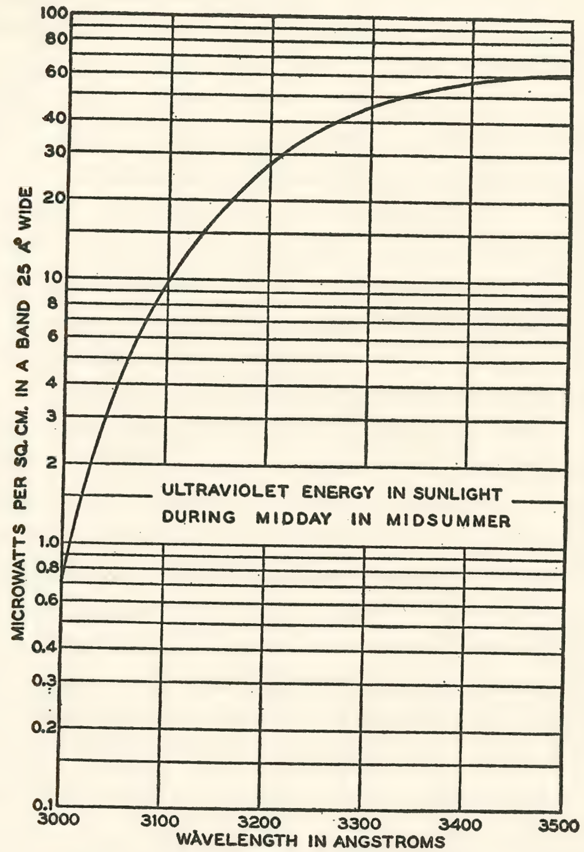


FIG. 15. The spectral distribution of energy in the short-wave half of the ultraviolet spectrum of sunlight averaged for typical clear days during summer months in the vicinity of Cleveland.

one readily realizes the great difficulties involved in making measurements. However, all these must be surmounted for the ultraviolet energy near the end of the solar spectrum is exceedingly important.

In Fig. 15 is presented the spectral distribution of energy in the short-wave half of the ultraviolet spectrum of sunlight during midday on what we consider to be reasonably typical clear days during the summer months. The curve is plotted on a vertical logarithmic scale in order

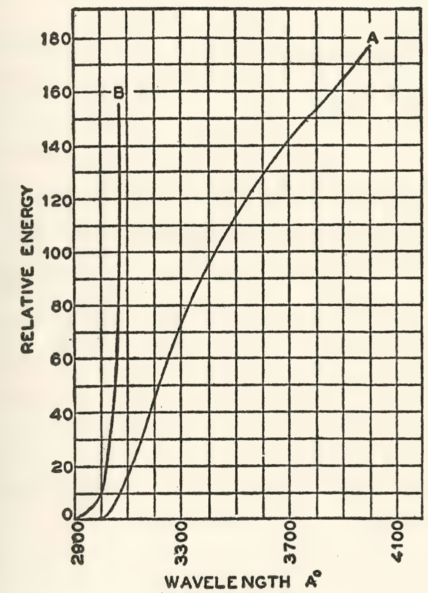


FIG. 16. A demonstration of the extreme steepness of the spectral energy distribution near the short-wave end of the solar spectrum. *B* is plotted on a scale 10 times that of *A*.

to encompass the great range in absolute values of energy. The data are for spectral bands 25 Angstroms wide. If data are desired for spectral bands 100 Angstroms in width, the energy values in 4 bands are added.

An idea of the steepness of the spectral energy distribution curve of sunlight is obtained from Fig. 16. For this purpose, only relative values of energy are presented. The curve labeled *B* is plotted on an ordinate scale 10 times that of the curve labeled *A*. Therefore, in considering *B* in con-

nection with the ordinate values the latter should be reduced to one-tenth. However, this illustration is introduced solely for the purpose of emphasizing the very steep rise in the spectral energy in the very important region shorter than λ3100.

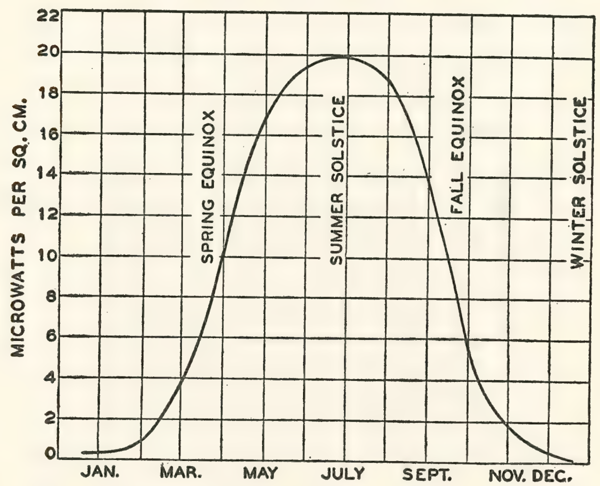


FIG. 17. Computations by Forsythe and Christison of solar energy shorter than λ3100 reaching the earth's surface during various months of the year. These values do not include skylight which is now known to contain much short-wave ultraviolet energy.

Forsythe and Christison [11] using the data of Abbot,[12] Fabry and Buisson,[13] and others computed the maximum solar energy in various spectral bands for a standard atmosphere of various air-masses corresponding to the altitude of the sun at noon at various periods of the year. Fig. 17 is plotted from the results of their computations. They found that the solar energy shorter than λ3100 which was received on a horizontal surface at noon in midsummer (air-mass = 1) was 24 microwatts per sq. cm. At noon in midwinter, with an air-mass of about 2.4, the computed

value was only 0.17 microwatt per sq. cm. However, these computations were based upon energy measurements near the short-wave limit of the solar spectrum which were not as dependable as those now available. Furthermore, these computations of solar energy obviously do not include skylight.

Elsewhere [1] the author weighed these computed values with others by Coblentz and Stair [14] and by Pettit [15] and with measurements by Greider and Downes,[16] and Luckiesh, Holladay and Taylor.[17] The conclusion at that time was that a value of 42 microwatts per sq. cm. was a reasonable value for the total energy shorter than λ3100 received by a horizontal surface at midday in midsummer on clear days at Cleveland.

Inasmuch as the computed values indicate that the amount of direct solar energy shorter than λ3250 is ten times the amount shorter than λ3100, it is obvious that experimental methods other than actual spectral energy measurements may differ considerably. Computations also may be misleading if they deal solely with direct sunlight. The sky contributes considerable erythemally-effective energy shorter than λ3100 which does not diminish with decreasing altitude of the sun as rapidly as this energy in direct sunlight does. However, all these methods and values have been helpful steps in the evolution of knowledge of sunlight and skylight.

In Table IV are presented the latest results by a colleague, A. H. Taylor, who has developed many devices for measuring radiant energy and has refined our techniques for many years. These results take into account both sunlight and skylight received on a horizontal surface during the midday hours on clear days in midsummer. The illumination of the surface due to the sun and sky averaged about 8500 footcandles. The contributions of skylight in the

ultraviolet region were determined by other means than direct energy measurements. The contributions of the sun in this spectral range were determined by measurements of spectral energy. Other data were also considered in determining the values presented in Table IV. It will be noted that the values are given for spectral bands 50 Angstroms wide. Therefore, if the total energy is desired shorter than a given wavelength or between any two wavelengths, it is only necessary to add the values in that range.

TABLE IV

Intensity of Energy or Radiant Power in Microwatts per Sq. Cm. on a Horizontal Surface During Midday on a Typical Clear Day in Midsummer in Cleveland, Latitude 41.5° N., for Each Spectral Band of 50 Angstroms Centered at the Various Wavelengths. The Intensity of Illumination on the Horizontal Surface Averaged About 8500 Footcandles of Combined Sunlight and Skylight

	Sunlight	*Skylight*	*Total*	λ	*Sunlight*	*Skylight*	*Total*
3000	2.6	2.6	5.2	5200	492	168	660
3100	24	23.5	47.5	5300	514	162	676
3200	65	60	125	5400	535	158	693
3300	108	96	204	5500	535	154	689
3400	126	107	233	5600	525	146	671
3550	144	115	259	5700	525	138	663
3700	186	139	325	5800	514	132	646
3850	192	136	333	5900	508	124	632
4000	268	165	433	6000	503	118	621
4100	339	209	548	6100	492	113	605
4200	377	223	600	6200	486	110	596
4300	404	213	617	6300	475	107	582
4400	426	201	627	6400	464	102	566
4500	453	216	669	6500	459	97	556
4600	492	234	726	6600	453	93	546
4700	514	229	743	6700	459	92	551
4800	525	218	743	6800	481	91	572
4900	525	207	732	6900	475	89	564
5000	525	193	718	7000	464	85	549
5100	508	184	692				

As discussed later, we determined the erythemally-effective energy received on a horizontal surface from the sun and entire sky over a continuous period of six years.

The dots on Fig. 18 represent the erythemal energy falling on the surface at noon on all sunny days for a period of two years, 1935 and 1936. The method and the results are described elsewhere by Luckiesh, Taylor and Kerr.[18] Values of the erythemal energy are expressed in E-vitons

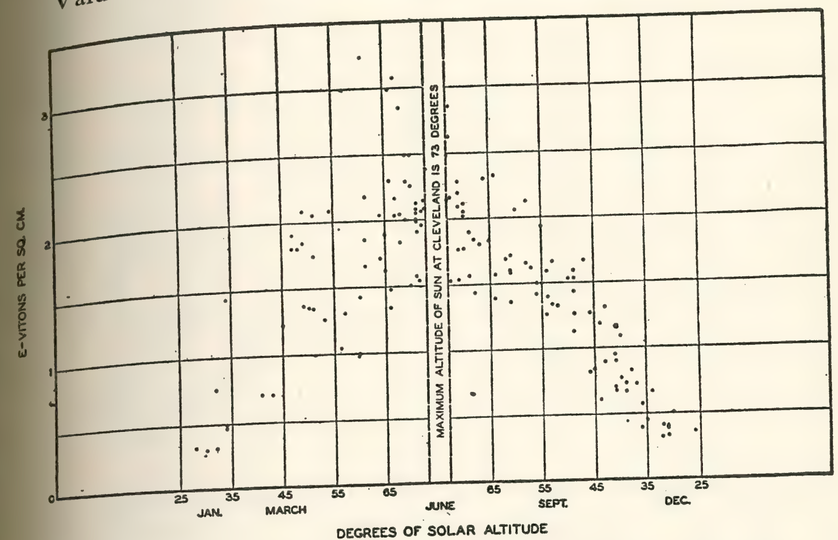


FIG. 18. Each dot represents a measurement of the erythemally effective energy contributed by the sun and entire sky to a horizontal surface during midday hours on all sunny days near Cleveland during 1935 and 1936.

per sq. cm. This unit, which was developed for the purpose, is completely described in a later chapter. Here it is sufficient to state that an E-viton is equivalent to 10 microwatts of energy at λ2967 in erythemal effectiveness. The unit provides a means of weighting spectral energy in accordance with its erythemal effectiveness just as spectral visible energy is weighted in accordance with its production of luminous sensation or light. One E-viton per sq. cm. incident for 40 minutes on average untanned skin produces an MPE or minimum perceptible erythema.

Fig. 19 differs from Fig. 18 in showing the effect of solar altitude during the day. The erythemal effectiveness of the energy received by a horizontal surface from both the sun and sky is expressed in E-vitons per sq. cm. from 9:00 A.M. until 5:00 P.M. on typical clear days in spring,

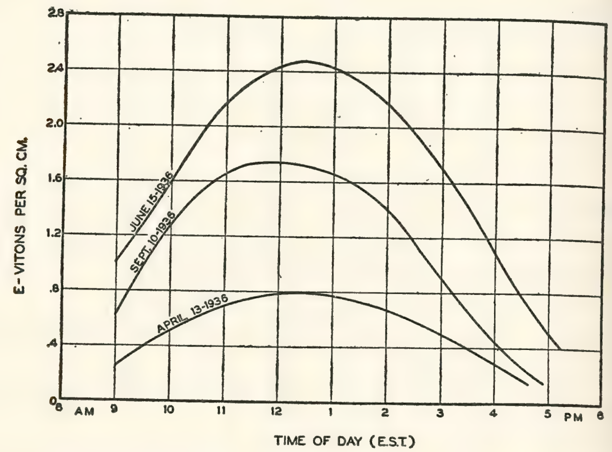


FIG. 19. Showing the effect of solar altitude upon the intensity of erythemally effective energy from the sun and entire sky on typical clear days in April, June and September in the vicinity of Cleveland.

summer and fall, respectively. Inasmuch as an E-viton per sq. cm. acting for 40 minutes on average untanned skin will produce an MPE, it is seen that the time required at noon on April 13 was about 50 minutes. At noon on June 15 only 17 minutes are necessary.

ERYTHEMAL EFFECTIVENESS OF SKYLIGHT

The ultraviolet energy from the sky has been generally ignored or neglected. That it is important is illustrated by Fig. 20 for two clear days, May 21 and September 10. The solar energy is readily eliminated by casting a small shadow on the sensitive cell used.[18] It is seen that on May 21 the

sky contributed more erythemal energy throughout the day than the sun, excepting for a period near noon. On September 10 the sky contributed much more erythemal energy throughout the entire day than the sun did. These measurements were made on a horizontal surface in the vicinity of Cleveland.

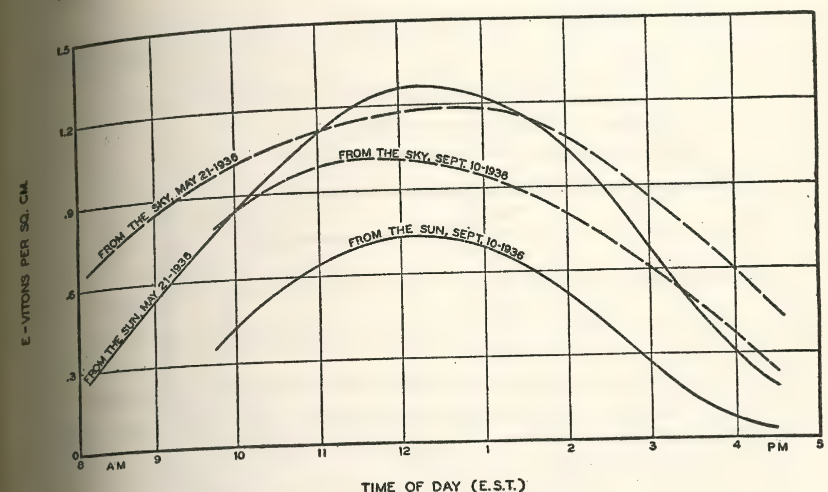


FIG. 20. The ultraviolet energy from the sky which is erythemally effective has been very generally ignored. Actually on clear days the entire sky often contributes more erythemal flux than the direct sunlight on a horizontal surface.

Many such records and other data testify to the effectiveness of skylight in producing erythema and tan, in preventing and curing rickets, and in other ways. Many persons have been surprised at the degree of sunburn acquired on the beach and elsewhere while shielding themselves from the direct sunlight. With such data as illustrated in Fig. 20, skylight from a large area of sky on clear and even hazy days may well be considered as a competitor of direct sunlight.

In Fig. 21 the sky-dome is illustrated and divided into 10-degree zones. It is seen that the upper zones are more effective in contributing energy to a horizontal surface than the lower zones. The percentages of the total ultraviolet energy for the various 10-degree zones and also for zones of equal area are indicated. Of course, if the receiving

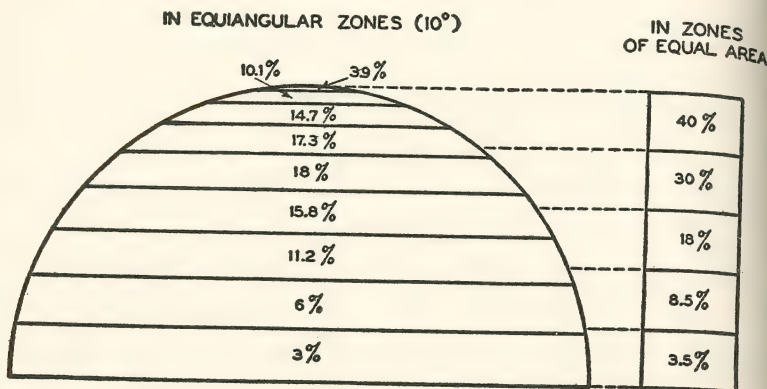


FIG. 21. Showing the percentages of erythemal energy reaching a horizontal surface from various zones of the sky from the horizon to the zenith. The percentages are presented for equal-angle zones and for equal-area zones, respectively, for typical clear days during the summer months.

surface is not horizontal, the contributions of the various zones are altered.

The relative intensities of erythemally-effective energy from equal areas of the sky in various zones from the horizon to the zenith are presented in Table V. These values are averages of measurements made in May, August and September for equal areas of clear sky in a direction perpendicular to each sky area, respectively. It is seen that the intensity of erythemally-effective energy from equal areas of sky does not fall off very rapidly from the zenith toward the horizon. This is also indicated in Fig. 20. The erythemal energy from the sun decreases far more rapidly

as the altitude of the sun decreases from the zenith toward the horizon. These facts pertaining to the erythemal effectiveness of skylight reveal the gross errors of ignoring the skylight and relying solely upon measurements and computations of direct solar energy.

TABLE V

Relative Ultraviolet Intensities of Equal Areas of Clear Sky at Different Distances from the Zenith for the Months of May, August and September. The Measurements Were Made in a Direction Perpendicular to Each Sky Area

Degrees from Zenith	*Relative Intensity*
0 to 10	100
10 to 20	87
20 to 30	85
30 to 40	81
40 to 50	79
50 to 60	74
60 to 70	64
70 to 80	52

From many measurements throughout the day on many clear days, the data plotted in Fig. 22 were obtained. It is seen that the erythemal energy from the sky on clear days *as measured on a horizontal plane* is greater than that from the direct sun for even high altitudes of the sun. When the sun is at low altitudes the contribution of erythemal energy to a horizontal surface by the entire sky is much greater than that by the sun. It is emphasized that these measurements are on a horizontal plane where the intensity of sunlight suffers greatly, owing to Lambert's law, when the sun is at low altitudes. The sky being always a dome in a fixed position, its contribution to a horizontal plane is constant, as far as Lambert's law is concerned, if the relative intensities of various sky areas remain unchanged.

A SIX-YEAR RECORD OF ERYTHEMAL EFFECTIVENESS

By means of an automatic recording device developed by A. H. Taylor, the erythemal effectiveness of radiant

energy incident upon a horizontal surface was summarized for each hour daily for a period of six years. Great care was exercised in the development of this device to obtain a spectral sensitivity equivalent to the spectral erythemal effectiveness of energy in the short-wave region of the

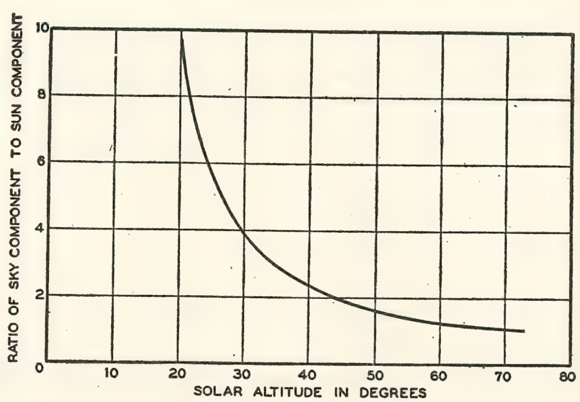


FIG. 22. Showing the ratio of the intensity of erythemal flux from the entire sky to that directly from the sun. These data are averages of measurements made on a horizontal plane on many clear days. Obviously the total erythemal flux from the entire sky, as measured on a horizontal plane, is greater than that contributed by direct sunlight even for high altitudes of the sun.

spectra of sunlight and skylight. Such a method yields valuable data for any source of ultraviolet energy which does not emit appreciable energy shorter than λ2800. Until more is known of the spectral effectiveness of ultraviolet energy for various applications, such methods will have to suffice. Naturally when ultraviolet energy is applied to human beings, erythemal effect upon the skin must be taken into account. This matter is discussed in detail in a later chapter.

Luckiesh, Taylor and Kerr [19,20] have recently summarized the results of this six-year continuous record of

measurements of erythemally-effective ultraviolet energy on a horizontal plane which received energy from the sun and entire sky. The hourly results combined into each month, respectively, are shown in Fig. 23. The records of the U. S. Weather Bureau for the same vicinity were also

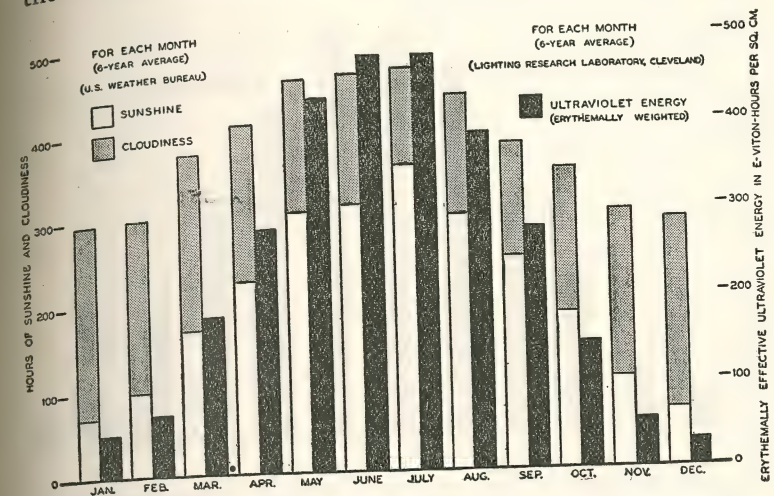


FIG. 23. Results of a continuous record of measurements of erythemally-effective ultraviolet energy (erythemal flux) on a horizontal plane which received energy from the sun and entire sky. The average hours of sunshine and cloudiness were compiled from the records of the U. S. Weather Bureau for the same vicinity (Cleveland).

summarized into months and averaged for the six years. As far as we know this is the longest continuous record available in terms of measurements that are meaningful. For the sake of interpretation it is repeated that a dosage of two-thirds of an E-viton hour per sq. cm. results in a minimum perceptible erythema, or MPE, on average untanned skin according to our determinations over many years.

In Fig. 24 are presented the percentages of the total annual erythemal energy for each month of the year. These

values are averages for each month for six years. The percentage of the total annual sunshine is also shown for each month averaged for six years. It is seen that the monthly percentages of total erythemal energy are generally greater for the fall months than for the spring months. However,

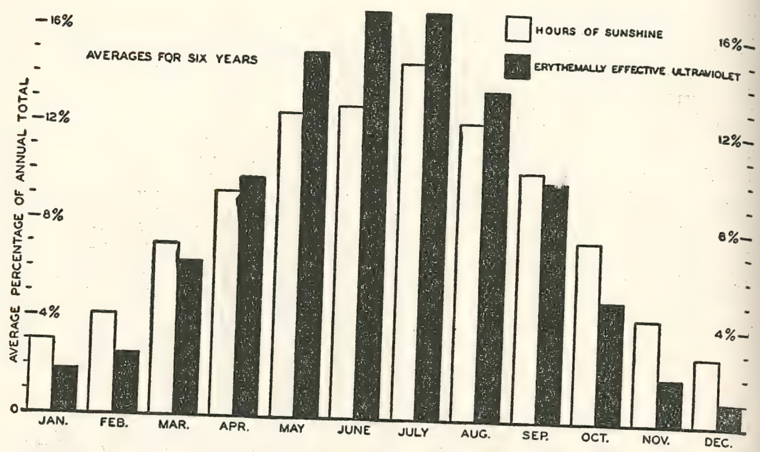


FIG. 24. Averages obtained from six years of continuous measurements of the total erythemally-effective ultraviolet energy reaching a horizontal surface directly from the sun and from the entire sky for each month of the year.

this generalization is neither safe nor important. It can be easily upset due to atmospheric conditions in a given geographical area where seasonal conditions are markedly different than elsewhere.

The data are presented in Table VI for each month for an average of six years. It is interesting to compare these monthly values with those in Fig. 17 which were computed for the sun alone. In the latter case no consideration of skylight is included.

The average total annual amount of erythemally-effective ultraviolet energy varied considerably during the

TABLE VI

Variation of Average Hours of Actual Sunshine per Month and of Erythemal Ultraviolet Energy in Daylight as Measured on a Horizontal Plane for a Six-Year Period in a Suburb of Cleveland, Ohio

	Hours of Sunshine			*Erythemal Ultraviolet Energy*	
Month	*Possible*	*Average*	*Percent of Possible*	** E-Viton Hours per Sq. Cm.*	*Percent of Total for Year*
January	295	71	24	51	1.8
February	297	98	33	72	2.5
March	370	167	45	182	6.3
April	401	221	55	280	9.8
May	452	298	66	430	15.0
June	455	305	67	476	16.7
July	461	350	76	476	16.7
August	429	292	68	386	13.5
September	374	243	65	277	9.8
October	343	178	52	143	5.0
November	295	103	35	55	1.9
December	285	66	23	30	1.0

* An exposure of approximately two-thirds of an E-viton hour per sq. cm. will produce an MPE.

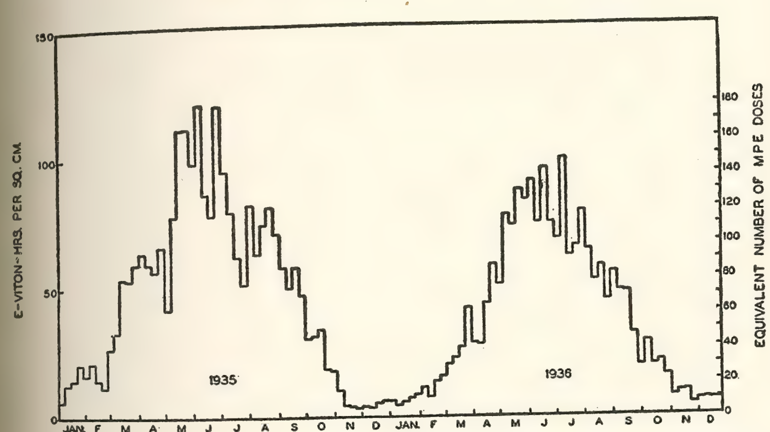


FIG. 25. The average total amount of erythemally-effective ultraviolet energy reaching a horizontal surface directly from the sun and entire sky for each week of 1935 and 1936.

six years. Of the years from 1935 to 1941, 1936 had the lowest value. The year 1939 had to be omitted for unavoidable reasons. In Fig. 25, 1935 and 1936 are compared on a weekly basis. For 1935 the total erythemal energy was 2907 E-viton hours compared with 2361 E-viton hours for 1936. The total MPE dosages for these two years were 4360 and 3540, respectively. The annual values for the six years are presented in Table VII expressed in MPE dosages. One of the latter is two-thirds of an E-viton hour per sq. cm.

TABLE VII

The Total Annual Number of MPE Dosages Received on a Horizontal Plane from Both the Sun and the Sky for Six Years

Year	*MPE Dosages*
1935	4360
1936	3540
1937	4090
1938	4125
1940	4900
1941	4720

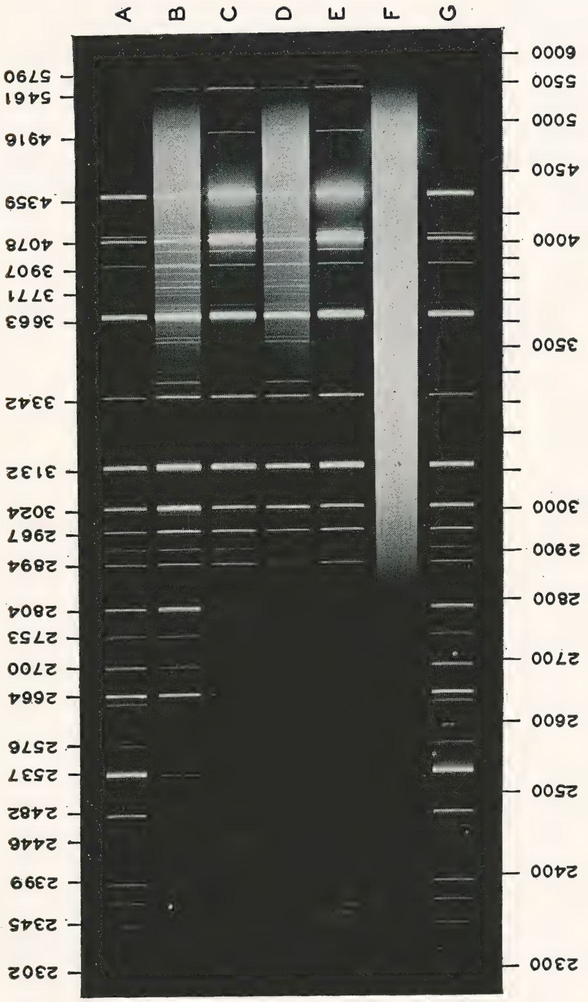


PLATE III. Spectrograms of visible and ultraviolet energy.

A. Quartz mercury-arc
B. S-1 sunlamp with Corex D bulb
C. Mercury-arc with 888 glass
D. S-1 sunlamp with 690 glass
E. Mercury-arc with 690 glass
F. 500-watt tungsten-filament 888 bulb
G. Quartz mercury-arc

Erythema and Tan

THE MOST obvious effect of short-wave ultraviolet energy in sunlight is sunburn or erythema. After sufficient exposure, tanning results in varying degrees depending upon the individual characteristics of the skin. The full biological significance of erythema is not known, but it must necessarily be taken into account in the practice of ultraviolet therapy upon human beings. Obviously, too great an area of skin on which severe erythema is produced is undesirable and actually endangers the welfare and even life of a human being. In fact the destructive effect upon superficial layers of living cells and tissue limits the dosages of ultraviolet energy for both animals and plants.

For many years the degree of erythema has been a guide to dosages applied in ultraviolet therapy. Erythema is the limiting factor in the everyday use of sunlamps. It must be the guide to the design of those installations of artificial sunlight which are likely to be widespread in the future. There is no reason why we should not bring some of the outdoors indoors. The beneficial effects of the ultraviolet component of sunlight can be provided by artificial means. Light for seeing can be accompanied by biologically-effective ultraviolet energy for health. This the author has termed dual-purpose lighting.[1,21] Such installations can be readily designed so as to produce a given degree of erythema in the longest daily period during which indoor workers would be exposed to it. It has been shown by H. J. Gerstenberger [22] that rickets can be prevented and cured by daily dosages of ultraviolet energy which are insufficient to produce a minimum perceptible

erythema (MPE) on untanned skin. Measurements of erythemal energy in sunlight and skylight also verify this conclusion.

The measurement of biologically-effective ultraviolet energy used to be so difficult that it could not be done by most of the medical profession which practiced ultraviolet therapy. As a result, many of the published results of therapeutic and biological benefits lack the great value of accurate spectral energy measurements. During recent years great advances have been made in developing relatively simple and sensitive devices. However, appraisal of dosages and sources of ultraviolet energy is bound to be made by the erythemal effect. Furthermore, many of the therapeutic and biological effects are deep-seated and indirectly achieved. In addition to these facts, knowledge pertaining to the spectral effectiveness of ultraviolet energy for many of these deep-seated and indirect effects is not available. For these and other reasons, erythemal effectiveness is a very important factor.

MAJOR EFFECTS OF ULTRAVIOLET ENERGY

It aids in appraising the importance of erythemal effectiveness to consider briefly some of the major direct effects of ultraviolet energy. Although they are treated in detail later, some of the plots of spectral effectiveness are shown in Fig. 26. The portions shown with broken lines indicate that knowledge or agreement is not entirely adequate. However, the maximum and the spectral region of effectiveness are fairly well established in each case.

The prevention and cure of rickets is well known to be due to ultraviolet energy near the short-wave limit of the solar spectrum. Apparently the maximum effectiveness of energy is near λ2967. Ultraviolet energy of shorter wavelengths from artificial sources also has antirachitic

value, but the effectiveness relative to λ2967 is not well established. It will be noted that the maximum near λ2967 closely coincides with the maximum of erythemal effective-

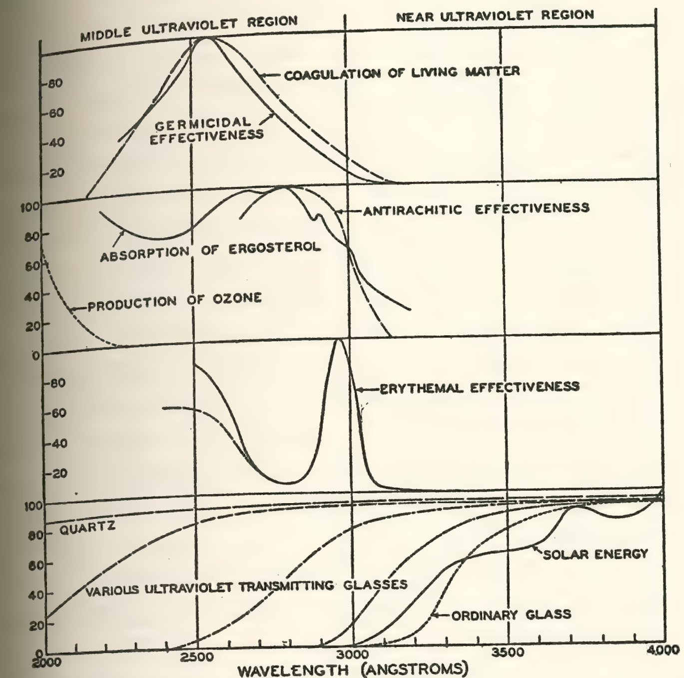


FIG. 26. Some major effects of ultraviolet energy of various wavelengths from the best data available. The lowest group of curves illustrates the control of ultraviolet energy, produced by artificial sources, which can be accomplished by means of glasses.

ness in that region. Therefore, erythemal effect is at least a rough appraisal of the antirachitic effectiveness of dosages and sources of ultraviolet energy whose short-wave limit is in the region of λ2800 or λ2900. The antirachitic value of energy shorter than λ2900 can readily be established by using a series of filters with the quartz mercury arc which

would limit the spectrum at various wavelengths between λ2000 and λ2900.

The same comments apply to the activation of ergosterol or the production of Vitamin D in living tissue of the skin as in non-living materials. In the production of Vitamin D on a commercial scale, quartz mercury arcs have long been used. A series of filters with different short-wave cutoffs, as illustrated in Fig. 29, could be used to determine the effectiveness of the ultraviolet energy between λ2000 and λ2900. There are indications that energy in the region of λ2500 and λ2600 is antirachitic through the production of Vitamin D. The use of germicidal lamps in poultry houses also yields some evidence in this respect.

The absorption of ergosterol for ultraviolet energy of various wavelengths indicates only the spectral region in which the activating energy is to be found. Grotthus's Law is commonly misinterpreted. According to this law, adequately proved as a basis for the principle enunciated by it, radiant energy must be absorbed to produce an effect. However, this does not mean that all radiant energy of various wavelengths that is absorbed produces a given photochemical or photobiological effect. This fact must be kept in mind when considering spectral absorption curves of ergosterol or of any other compound. (See Plate II.)

Inasmuch as the antirachitic effectiveness of ultraviolet energy apparently springs from the production of Vitamin D in fatty substances, the spectral absorption curve of ergosterol, plotted in Fig. 26, has some significance. This is also true of the spectral absorption curves of other compounds whether considering beneficial or deleterious effects of ultraviolet energy.

As shown later, the germicidal effectiveness of ultraviolet energy of various wavelengths is fairly well established. Its maximum is in the region of λ2500 to λ2600. The coagulation of egg-albumen and other living matter probably is closely allied to the destruction of germs and of other living matter. Therefore, the spectral effectiveness is plotted in Fig. 26 in connection with germicidal effectiveness.

These are merely glimpses of the initial major effects of ultraviolet energy which aid in appraising the significance of erythemal effectiveness as well as its limitations. It has been shown by H. J. Gerstenberger [22] that dosages of ultraviolet energy insufficient to produce even a minimum perceptible erythema (MPE) prevent and cure rickets. Erythema can be produced in various degrees up to a vivid red which results in complete destruction of the outer layers of the skin. These degrees cannot be very accurately gauged or described. Therefore, the author and his colleagues have found it convenient to deal with MPE in fractions and multiples determined by variations in time of exposure of the skin to a given intensity of erythemal energy.

Dosage is primarily a matter of time times intensity. Actually in certain therapeutic effects which are indirect results of exposing the skin, such as cure of rickets and tuberculosis of the bone, the area of the exposed skin must be considered to be an additional factor in dosage. For example, if rickets are prevented by increasing calcium metabolism by the production of Vitamin D in the fatty subcutaneous layers of the skin, the amount of Vitamin D produced by a given intensity of ultraviolet energy for a given time, depends upon the area of skin exposed.

REFLECTION OF HUMAN SKIN

The color and spectral reflectance of human skin depend principally upon race, environment, exposure and

susceptibility to tanning. Unless otherwise indicated, all the data presented here were obtained with socalled white persons of the Caucasian race. We have tested the skin of many subjects over many years, thereby acquiring experience in determining what may be considered to be average subjects. In fact, it becomes possible to predict with a considerable degree of accuracy the susceptibility to erythemal energy and the probability of tanning by a casual observation of the subject. With such experience one can generally point out the subjects who will readily "burn" with little or no resulting tan.

Although individuals vary greatly in the appearance of their skin, the variation in the reaction of their untanned skin to erythemal energy does not vary as much. The appearance and susceptibility of skin on various parts of the body vary considerably due to its environment and previous exposure to ultraviolet energy. Any convenient area can be used for relative measurements. However, if fundamental and reasonably absolute measurements are desired, untanned skin should be used. We have found it convenient and reasonably satisfactory to use the skin on the upper arm. This area is generally protected in everyday exposure outdoors. Unless otherwise stated this is the area of skin used.

The reflectance or reflection-factor of untanned skin of white persons generally does not vary greatly among a group of persons unless there are representatives of small groups whose skin characteristics are extreme. For example, the reflection-factors of the untanned skin for light or visible energy for three persons, rated as a socalled blond, a moderate brunette and an intermediate, were 51, 48 and 52 percent, respectively. In other words, the untanned skin of the upper arm for most white persons reflects about one-half the incident light.

The reflection-factor of untanned skin for ultraviolet energy is much lower than for light or visible energy, and for erythemal energy is very low. The average values for energy of various wavelengths are presented in Table VIII as determined for a representative group of subjects. It is seen that only 4 to 11 percent of the erythemal energy from $\lambda 2800$ to $\lambda 3200$ is reflected by average untanned skin of the upper arm. In other words, from 90 to 95 percent of

TABLE VIII

Percentages of Incident Energy Reflected by Average Untanned Skin of White Persons

(Luckiesh, Taylor and Holladay)

Wavelength	*Percent*	*Wavelength*	*Percent*
2400	3	4000	28
2600	4	4500	35
2800	4	5000	42
3000	5	5500	48
3200	11	6000	54
3400	16	6500	65
3600	21	7000	68

this erythemal energy is absorbed by white untanned skin. The absorption-factor of the skin for energy of a given wavelength is 100 minus the reflection-factor for that wavelength when these values are expressed in percent. Although the skin of a colored person reflects much less light or visible energy than that of a white person, the difference is not nearly so marked for erythemal energy. In fact the skin of a colored person will exhibit an erythema under exposures comparable to those which produce the same degree of erythema on the skin of a white person if neither has been greatly exposed to sunlight outdoors.

As already stated, there is less variation in the reflectance of the skin for ultraviolet energy than for visible energy. This is partly due to variation in pigmentation owing to various degrees of tan. It is also due to the varia-

tions in depth of penetration of the incident energy of the skin of different individuals and of different areas of skin of the same individual.

In Fig. 27 are shown the reflection-factors for energy of various wavelengths of the untanned skin of a fairly

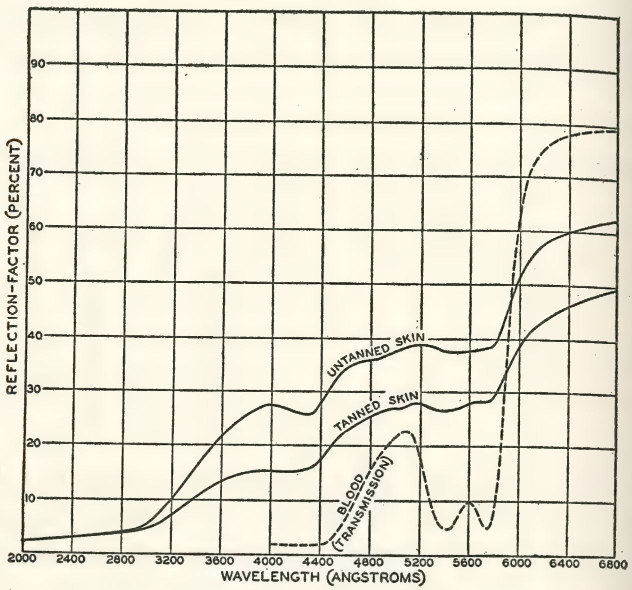


Fig. 27. The reflection-factors of tanned and untanned skin of a fairly representative white person for ultraviolet and visible energy of various wavelengths. The spectral transmission of a thin layer of blood is also shown. Its influence upon the spectral reflectance of white skin is evident.

average subject. Tne spectral reflection-factors are also shown for moderately tanned skin of the same subject. Actually the spectral reflection curve, particularly in the visible region, is affected by light penetrating into the flesh and then being more or less selectively reflected. The curves in Fig. 27 reveal the influence of certain absorption and transmission spectral bands of the blood. These bands

are visible in some degree in the spectral reflection characteristics of the skin.

TRANSMISSION OF THE SKIN

The skin of different areas of the body varies enormously in the thickness of the outer horny layer. However, these differences are not very marked over much of the body where the skin is not subjected to hard usage and severe exposure to the sun and wind. For most of the skin, the penetration of ultraviolet energy may be described as follows:

λ2000 to λ3200 penetrates very little, but kills surface organisms and can destroy the surface layer of skin.
λ2000 to λ2500 penetrates the horny layer (corneum) and produces some erythema.
λ2500 to λ2800 penetrates basal cells (stratum granulosum), produces some pigment, and produces erythema.
λ2800 to λ3200 penetrates the blood-vessel network (rete vasculosum), producing considerable pigment and erythema, stimulates sweat glands and sympathetic nerves.
λ3200 to λ3900 penetrates the corium, produces tan with relatively little erythema.
λ3900 to λ14,000 penetrates and heats subcutaneous tissues, causing a reddening known as hyperemia which is an excess of blood in the network of capillaries and is quite different from erythema.

Beginning with the surface of the skin, the principal layers at increasing depth are the horny layer or corneum, the basal cells or stratum granulosum, the network of blood-vessels or rete vasculosum, the corium and the subcutaneous tissue.

The transmission-factors of thin layers of skin, as determined by Hasselbach,[23] are presented in Table IX for most of the principal wavelengths of the mercury spectrum. The transparency of the skin decreases with decreasing wavelength, but considerable energy can penetrate to a depth of more than 0.1 mm. However, the erythemal and antirachitic energy, λ2800 to λ3200, does not penetrate in

appreciable quantities to a depth of 0.5 mm. Actually, very little energy is necessary provided the exposure is long enough. However, the data indicate the desirability of exposing the areas of skin that are devoid of thick horny layers and are particularly transparent.

TABLE IX

Percentages of Energy of Various Wavelengths Which Pass Through Skin of Different Thicknesses in Millimeters

(Hasselbach)

Wavelength	*Percent Transmitted* 0.1 mm.	0.5 mm.	1.0 mm.
2894	0.01		
2967	2		
3024	8		
3132	30	0.3	0.008
3342	42	1.3	0.02
3663	49	3	0.08
4050	55	5	0.3
4359	59	7	0.5

The spectral transmission curve of a thin layer of blood in Fig. 27 indicates the transparency of human flesh to long-wave visible energy. Owing to the great percentage of water in the bodily tissue, the transmission of infrared energy is generally confined to that region just beyond the visible spectrum and extending to about $\lambda 14{,}000$.

ERYTHEMAL EFFECTIVENESS OF ULTRAVIOLET ENERGY

In determining the erythemal effectiveness of ultraviolet energy, it simplifies the complex problem considerably to use untanned skin which does not have a thick outer horny layer. Certainly one would not choose the sole of a foot or the palm of a hand. The horny layer on these parts is thick and variable. One would not choose tanned skin, for there are various degrees of tanning which cannot be accurately measured or described. In accurate work it is

well to avoid the use of skin that has been exposed to sunlight even months before. Therefore, in considering all these aspects and taking into account the factor of convenience, we have chosen to work with the skin on the upper arm. In much preliminary work it is well to use the skin on the back in order to save the arm for final results.

We use opaque masks with a series of holes a few millimeters in diameter. After the erythema and the resulting tan have disappeared, the circular areas previously exposed can be seen when illuminated in a dark room with long-wave ultraviolet energy or socalled black light. The areas which have been previously exposed to produce an erythema, even though they exhibit no visible differences from the surrounding skin under ordinary light, appear as darker spots amid the surrounding skin which fluoresces under socalled black light. Apparently the effect of erythema is to destroy much of the ability of the skin to fluoresce for many months after the original exposure.

After years of experience with many subjects, one acquires some ability to choose reasonably average subjects with average untanned skin. There is no standard way of describing this average individual or skin. However, anyone engaged in this kind of work or in ultraviolet therapy can standardize the time and intensity for average untanned skin as determined by experience. This is a part of our technique. However, in selecting a new group of subjects, even with the advantage of long experience, some subjects are likely to be at least twice as susceptible as other subjects. The data presented in this and other chapters may be considered to represent the results with average untanned skin of the upper arm unless otherwise stated.

In Fig. 28 are plotted the results obtained by Hausser and Vahle,[24] Coblentz, Stair and Hogue[25] and Luckiesh, Taylor and Holladay.[21] It will be noted that the data are

in excellent agreement for the maximum near λ2967 and in the vicinity of that wavelength. The differences are considerable for energy of wavelengths shorter than λ2700. This is due partly to the greater difficulty of making absolute measurements of ultraviolet energy a decade or more

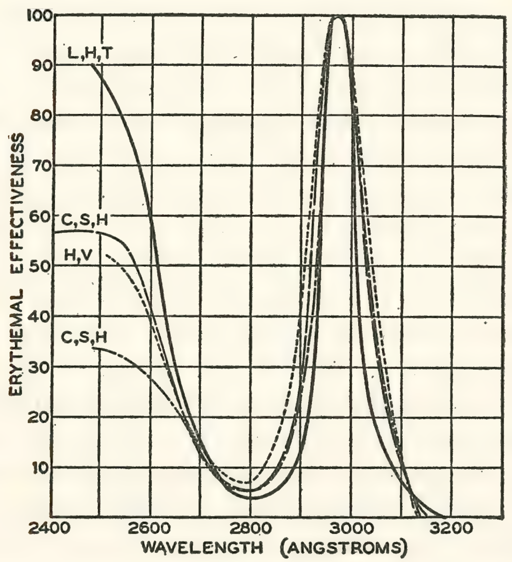


Fig. 28. The erythemal effectiveness of ultraviolet energy as determined by various investigators.

ago. However, another reason for the differences lies in the fact that erythema produced by energy in this region is more evanescent than that produced by energy of longer wavelengths. For example, if the erythema is judged a few hours after exposure of the skin, the erythemal effectiveness of λ2400 to λ2600 is found to be greater than if the erythema is judged a day after exposure. More recent experience with germicidal lamps which emit ultraviolet energy almost entirely in the region of λ2537 leads us to believe

that the results obtained by the author and his colleagues are the more practical and representative. These are presented in Table X. The International Commission on Illumination has standardized values of erythemal effectiveness which, in the region of λ2400 to λ2800, are approximate averages of the data presented in Fig. 28. For reasons given, we prefer the data for this region as presented in

TABLE X

Relative Erythemal Effectiveness of Ultraviolet Energy for Average Untanned Skin

Wavelength	*Erythemal Effectiveness*	*Wavelength*	*Erythemal Effectiveness*
2399	95	2804	6
2482	90	2894	25
2537	80	2925	70
2576	70	2967	100
2654	30	3024	50
2675	20	3132	2
2700	15	3342	0.4
2760	5	3663	0.12

Table X. It will be noted that energy of λ2967 or λ2500 is nearly a thousand times as effective in the production of erythema as energy of λ3663. This is in agreement with the later conclusions of Hausser.[24] In the region of λ2800 the spectral erythemal data are probably least dependable owing to the fact that there are no strong mercury lines available.

It is relatively easy to determine an MPE, or minimum perceptible erythema, from a series of exposures on a series of small areas of skin. Without a photometer or colorimeter it is not possible to judge different degrees of erythema above the threshold or minimum perceptible. Anyone can establish for himself several degrees of erythema which may not be readily described to others but which are useful. Four degrees used by the authors and his colleagues, and

the approximate relative exposures of untanned skin to erythemal energy which produce them, are as follows:

Degree 1, Minimum perceptible erythema (MPE)........	1
Degree 2, Vivid erythema, producing some tan...........	2.5
Degree 3, Painful burn..................................	5
Degree 4, Blistering.....................................	10

These values are only approximate and they are modified somewhat by the degree of pigmentation. The range of time between the extreme degrees is somewhat less for sources emitting considerable ultraviolet energy shorter than $\lambda 2900$ than for sources, such as natural sunlight, which emit no appreciable energy shorter than $\lambda 2900$. Incidentally, we have found that the reciprocity law holds over a large range of time and intensities. We have proved this for a range of 1 to 16, and have indications that the law holds at least approximately over a much larger range.

ERYTHEMA VERSUS TAN

As already indicated, ultraviolet energy penetrates farther into untanned skin as the wavelength increases. This penetration has much to do with the production of tan. We may consider tan to be pigment of the blood which has been left stranded in the network of blood vessels after the high tide of blood has receded. The process is not as simple as this, but it is a fact that tanning is more effectively produced by ultraviolet energy which more deeply penetrates beyond the outer layers of the skin.

Erythema or sunburn does not appear for some time after the exposure of untanned skin to the ultraviolet energy. However, as the wavelength increases from $\lambda 2967$, longer and longer exposures are necessary. For energy longer than $\lambda 3200$, the resulting erythema becomes more of a copper color than the vivid red due to energy of shorter wavelengths. Actually, the spot may appear colored before the longer exposure is completed. In other words, what we see is more of a tan than merely an erythema. Therefore, a sunlamp for tanning should supply an abundance of ultraviolet energy of longer wavelengths than $\lambda 3000$. This is why sunlight and skylight are so effective in producing tan. This is also the principle of socalled sun-tan lotions. They merely absorb the short-wave ultraviolet energy so as to minimize the erythema without reducing the tanning effectiveness of the energy of longer wavelengths.

The reddening of the skin on exposure to radiant energy may be due to erythema or hyperemia or both. Erythema is a reddish inflammation of the skin and does not appear until some time after exposure to ultraviolet energy of certain wavelengths, generally shorter than $\lambda 3200$. It involves partial or complete destruction of the outer layers of the skin. Hyperemia is a reddening of the skin due to a temporary excess of blood in the network of small vessels. Hyperemia appears rather quickly after the beginning of an exposure to adequate energy. It is readily produced by short-wave infrared energy and by visible energy. It appears to be involved in the efficient production of tan by sunlight and its artificial equivalents.

Tanning is not thoroughly understood and it cannot be taken as a measure of health. However, one who has had much experience with erythema and tan often finds it difficult not to associate good health and a rugged constitution with a person whose skin readily tans. However, tan in everyday life is more of a protection and an esthetic consideration than a symbol of health. A deep tan or the deep pigmentation of a colored person apparently does not prevent exposures to ultraviolet energy from producing its beneficial effects such as curing and preventing rickets.

Negro skins apparently have the power to produce pigment unaided by ultraviolet energy. Albino skins do not have this power even with the aid of ultraviolet energy. One theory is that two substances are needed to produce pigment and that the negro skins unaided supply both to a marked degree, although they can become tanned darker than normal by exposure to ultraviolet energy. Of course, these skins can develop erythema or sunburn. Albino skins aided by sunlight may be able to supply one of these substances, but not the other. Normal white skins appear to be between these two extremes. In these cases perhaps the skin supplies one substance unaided and produces the other with the aid of sunlight. This same theory may also account for the difference in the degree of tan caused by ultraviolet energy of different wavelengths. Solar energy between λ3000 and λ3200 produces a rich brown pigment perhaps aided by the hyperemia and dilated blood capillaries.

Depigmentation or the loss of tan by the normal skins of whites takes place more or less slowly, depending upon the initial degree of pigmentation. The cells in which the pigment has been produced are unable to produce pigment without the aid of ultraviolet energy. As the cells divide, the new cells apparently contain only one-half the pigment of the original cells. This process of subdivision apparently results in a mathematical fading of the tan. Some of the cells die and they and their pigment are drained off. Other cells are pushed to the surface and are rubbed off. Eventually the skin is free of this evanescent pigment.

TANNING EFFECTIVENESS OF ULTRAVIOLET ENERGY

Owing to the scientific and practical importance of the effectiveness of ultraviolet energy from λ3000 to λ3600, we have devoted considerable research to this spectral region. No extensive determinations of the erythemal and tanning

effectiveness in this region had been made notwithstanding the fact that this is the region of great importance in considerations of natural and artificial sunlight. Since then Hausser [24] has published some results pertaining to long-wave ultraviolet energy. All our other published data are averages of various investigations with groups of subjects totaling a large number. In determining the erythemal and tanning effectiveness [26] in the region from λ3000 to λ3600, special techniques were necessary which appear to be worth describing in some detail.

Eighteen fairly average male adult white subjects were used. Their ages were generally between 25 and 35 years, and they included a range of types of socalled blonds and brunettes. Since it is difficult to obtain monochromatic ultraviolet energy of sufficient intensity to produce tanning, if its tanning effectiveness is low, we used filters with various degrees of transparency to radiant energy of various wavelengths. Seven such filters were chosen, their descriptions being given in Table XI and their spectral transmis-

TABLE XI

Filters Used in the Determination of the Spectral Tanning Effectiveness of Ultraviolet Energy

Filter	*Thickness*	*Type of Glass*
A	1.0 mm.	Pyrex
B	2.1	Unknown
C	4.0	Corex D
D	3.0	Pyrex
E	6.1	Ordinary plate
F	9.35	Corning Blue-Fluorescing
G	11.45	Ordinary plate

sion curves in Fig. 29. The ultraviolet sources were bare Type S-1 lamps contained in clear quartz and Corex D bulbs. This source, as illustrated in Fig. 6, consists essentially of a mercury arc operating between incandescent tungsten electrodes.

In most of the tests the subject was irradiated on the inner side of his upper arm through an 8 mm. hole in an

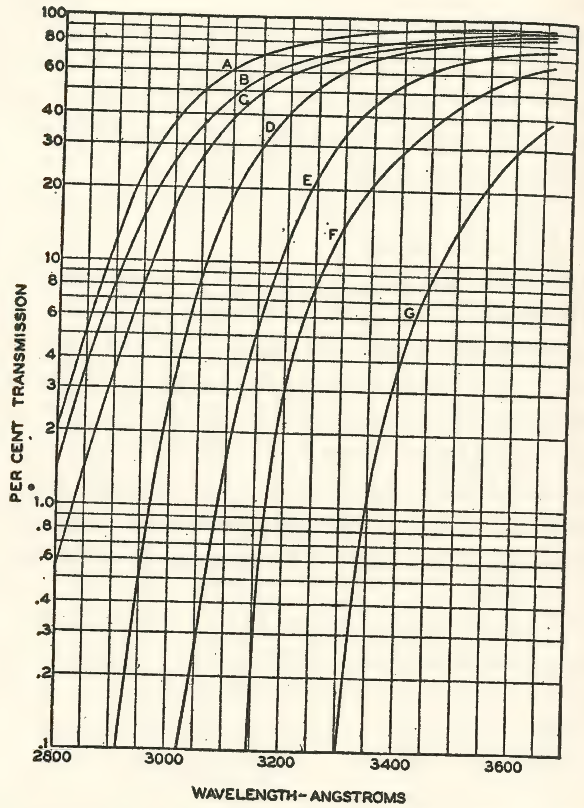


FIG. 29. Spectral transmission-factors of a group of useful glass filters of various compositions and thicknesses.

A, Pyrex 1 mm.
B, Unknown 2.1 mm.
C, Corex 4 mm.
D, Pyrex 3 mm.
E, Ordinary plate glass 6.1 mm.
F, Corning blue-fluorescing 9.35 mm.
G, Ordinary plate glass 11.46 mm.

opaque screen. The image of the arc of the Type S-1 lamp was focused on the hole by means of quartz lenses, a water-cell with quartz walls being interposed to remove most of

the infrared energy from the beam. In the first series of tests five spots on the inner upper arm of each subject were exposed to the energy from the lamp filtered through one of the filters illustrated in Fig. 29. Each spot was exposed for a different period of time. Four filters, *A*, *B*, *C* and *D*, were included in this test and twenty spots, in four parallel rows, were exposed on each subject. Representative subjects were exposed in this way; then some changes in the focusing of the lamp were made and fourteen other subjects were exposed in the same way. Representative subjects were also exposed with filters *C*, *E*, *F* and *G*. Owing to the long exposures required, it was impracticable to use a large number of subjects in this latter part of the investigation.

The appearance of the exposed spots is dependent upon the wavelength of the energy to which they have been exposed. In those cases where the total effect is predominantly due to energy in the spectral region $\lambda 2950$ to $\lambda 3150$, there is no immediate visible effect, but after a few hours a definite erythema appears which is followed in a few days by subsidence of the inflammation and formation of tan. In the case of exposures through filters transmitting only those wavelengths longer than about $\lambda 3300$, the spots appear somewhat brownish or tanned immediately after exposure, followed later by some erythema together with the tan. Thus it appears that there is a definite latent tanning effect in the former case, which may or may not also be present in the latter case. Two spots showing the same contrast with the unexposed skin 24 hours after exposure will in general appear approximately equal to each other a week later, after the erythema has subsided and tan has fully developed, even though one spot may be produced principally by radiant energy in the region $\lambda 2950$–$\lambda 3150$ and the other principally by radiant energy of approximately $\lambda 3650$. These various observations lead us to believe

that for wavelengths longer than λ2950 the spectral erythemal effectiveness curve cannot be separated from the tanning effectiveness curve, at least for such tanning effects as may be apparent within 12 hours, when the erythema has approximately reached its maximum.

The erythemal and tanning results were appraised by examination of the subjects immediately after exposure, on the next day, and at weekly intervals thereafter. The results were judged not only by the "minimum perceptible spot" but also by comparison of exposures required for all spots of equal erythema or tan. These weekly appraisals were made to determine whether there was any difference in rate of fading of spots obtained by exposures through different filters. We had expected to find a progressively decreasing rate of fading with filters *A* to *G*, since erythema and tan were principally due to increasingly longer wavelengths in this series of filters, for it is commonly assumed that tan is principally due to wavelengths longer than those which cause maximal or pronounced erythema. However, we found no appreciable differences in rate of fading of the erythema and tan produced with the various filters. This leads to the conclusion that for wavelengths longer than λ2950 the spectral erythemal and tanning effectiveness curves are practically identical. In fact, as the wavelength of energy increases, erythema appears to merge into tan and they appear to become "one and the same thing."

With data pertaining to the spectral energy of the lamp, transmission of the filter and exposure time to produce equal erythema or tan with various filters, it is possible to set up mathematical equations involving only the effectiveness of the radiant energy of different wavelengths as unknown quantities since we are dealing with sources emitting energy confined to a limited number of wavelengths in this region. However, it was generally found to be more practicable to substitute trial values for the effectiveness constants for different wavelengths in the simultaneous equations and to solve for the relative exposures required to produce equal tan with the different filters. These results were then compared with the experimentally determined exposures. Fairly definite relative values for the lines λ3130, λ3342 and λ3663 had been obtained from the test with filters which did not transmit energy of shorter wavelengths and it was assumed that the most probable values for all wavelengths would lie on a fairly smooth curve. Various solutions were tried, each one giving additional information as to which part of the curve needed revision to improve the agreement between observed and computed results. The tanning effectiveness curve finally adopted was the one providing the best agreement between computed and observed exposure ratios to produce equal tan, based on examinations of all subjects for periods from 4 to 10 weeks after exposure.

In Fig. 30 our determinations of the tanning effectiveness of energy from λ3663 to λ2967 are plotted as an extension of our determinations of the erythemal effectiveness of energy from λ3130 to λ2400. We have tied together our data on tanning to our data on erythema in the region of λ2804 and λ2894 by assuming that, in this region, tanning effectiveness is the same as erythemal effectiveness. We see no other way of treating the two phenomena, one of which dissolves into the other as the wavelength of energy decreases or increases.

Table XII shows the contribution of energy of different wavelengths to the total tanning when each of the seven filters is used with the quartz mercury arc. The actual exposure time varied from approximately 15 seconds with filter *A* to 75 minutes with filter *G*. We have assumed that

the reciprocity law (time × energy intensity = a constant) holds for these exposures and that effects due to different wavelengths are additive. We have previously found that

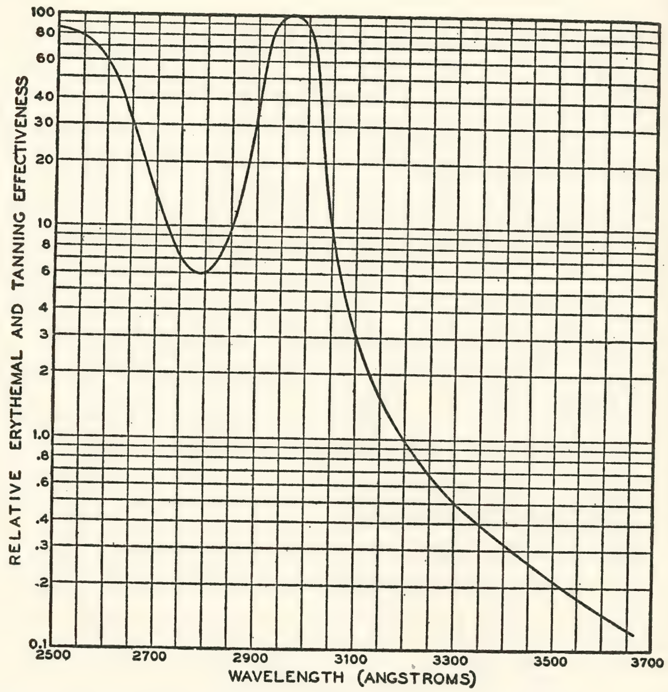


FIG. 30. The relative tanning effectiveness of energy from λ3663 to λ2967 is plotted as an extension of the relative erythemal effectiveness of energy from λ3130 to λ2500.

the reciprocity law holds for erythemal effectiveness over a range of 1 to 16 in intensity of energy with indications that it holds fairly well over a much larger range.

We believe that the erythemal and tanning effectiveness curves are practically identical for wavelengths longer than λ2950. The only evidence we have which seems to disagree with this conclusion is the fact that in one series

of tests with filters *C*, *E*, *F* and *G*, examination of the exposed spots ten weeks after exposure showed that those exposed through filter *C*, where most of the effect was due to energy at λ3022, had faded slightly more than those exposed through the other filters, where most of the tanning was due to longer wavelengths.

TABLE XII

Contribution of Different Spectral Lines to the Total Tanning with Quartz S-1 Lamp and Seven Filters

	Percent of Total Tanning						
Wavelength in Angstroms	*Filter A*	*Filter B*	*Filter C*	*Filter D*	*Filter E*	*Filter F*	*Filter G*
2804	0.1	0.1					
2894	1.2	1.1	0.7				
2967	33.4	31.4	25.6	9.7			
3022	55.8	56.0	58.9	53.2	6.1		
3130	8.3	9.7	12.3	27.3	24.7	1.3	
3342	0.2	0.3	0.4	1.8	7.7	5.8	0.4
3663	1.0	1.4	2.1	8.0	61.5	92.9	99.6
Relative exposure for equal tanning	1	1.5	2.2	8.2	46	80	144

There was an obvious difference in the appearance of spots irradiated through filters *C*, *E*, *F* and *G*. Immediately after the exposure was completed, the spots irradiated through *F* and *G*, where the tanning effect was principally due to λ3663, had a slightly tanned appearance, whereas those exposed through filters *C* and *E* did not become visible until several hours after exposure and then exhibited the characteristic erythemal redness. When examined about 20 hours after exposure all spots showed some of the characteristic erythemal redness, but those exposed through filters *F* and *G* appeared reddish brown and were appreciably less inflamed than those exposed through *C* and *E*. Consequently, comparisons of spots at the first examination were based on *equal contrasts* with the unexposed adjacent

skin. Apparently the longer wavelengths, especially λ3342 and λ3663, produce a direct or immediate tan or its equivalent with less inflammation than that produced by the shorter wavelengths.

If the tanned skin is examined under ultraviolet energy from a source such as the Type S-1 lamp equipped with a filter which transmits λ3663 freely but absorbs most of the visible light (Corning Red Purple Ultra filter), it is found that the irradiated area appears darker than that which has not been exposed even when no effect is visible under ordinary light. Apparently the exposure reduces the fluorescence of the skin and this makes the spot appear darker than the adjacent skin under the ultraviolet energy. We have used this method for years in examining irradiated spots and in determining something of the skin's history. Spots irradiated through filters *F* and *G* were visible in this way immediately after exposure, whereas those exposed through filter *C* were not apparent in this manner for several hours after exposure. Furthermore, spots which have been exposed and tanned by ultraviolet energy of any wavelength are still visible under this ultraviolet illumination long after they have become invisible under ordinary light many months after exposure.

These results lead us to believe that under certain circumstances there may be a simultaneous production of erythema and tan, but that the presence of the tan may be obscured by a strong erythema. This is especially true in the case of natural sunlight, where there is a great deal of energy in the region which we have found to produce direct or immediate tan. As a consequence, it is probable that the "erythemal effectiveness" curve heretofore tentatively accepted is actually a combined erythemal and tanning curve for wavelengths longer than about λ3000. Our data presented in Fig. 30 and Table X revise and extend

this spectral erythemal curve because in previous researches the energy intensities and exposures in this region have been insufficient to produce suitable erythema or tan for adequate study of this spectral region.

Since our researches on tanning effectiveness were completed, we have reviewed a paper on this same subject by Hausser.[24] He focused the ultraviolet spectrum from an intense arc on the skin through what was essentially a quartz spectograph. He concluded that in addition to the erythema produced by energy in the region of λ2980, there is shown in the region λ3300–λ4200 the formation of another strong, deep-red erythema, whose long wavelength boundary apparently falls off sharply at λ4200. He also concluded that there is a strong maximum at λ3800 and two weaker maxima at λ3600 and λ4080. Apparently no spectral tanning effectiveness curve was derived and one can be misled by the mixture of hyperemia with true erythema and tan which are the results of the necessarily long exposures to the long-wave ultraviolet energy. However, Hausser's observations as to the character of the erythema produced by different spectral regions, and the immediate appearance of tan or browning of the skin due to exposure to energy in the region of λ3650, are in general agreement with our observations. He reported that it requires about 500 times as much energy at λ3800 as at λ2967 to produce an MPE. We found that for the production of equal amounts of tan, observed 10 weeks after exposure, the exposure ratios (energy × time) at λ2967 and λ3663 must be in the ratio of approximately 1 to 800, which is of the same order of magnitude as Hausser's conclusion.

In Fig. 31 are shown the spectral reflection of the skin, also the spectral transmission [23] and absorption by 0.1 mm. of skin. Since energy must be absorbed to produce erythema or tan, they are related in some way to the depth of

penetration of the energy or to an intermediate effect of the incident energy. Erythema due to wavelengths in the spectral region, λ2500–λ2700, is quite superficial and dis-

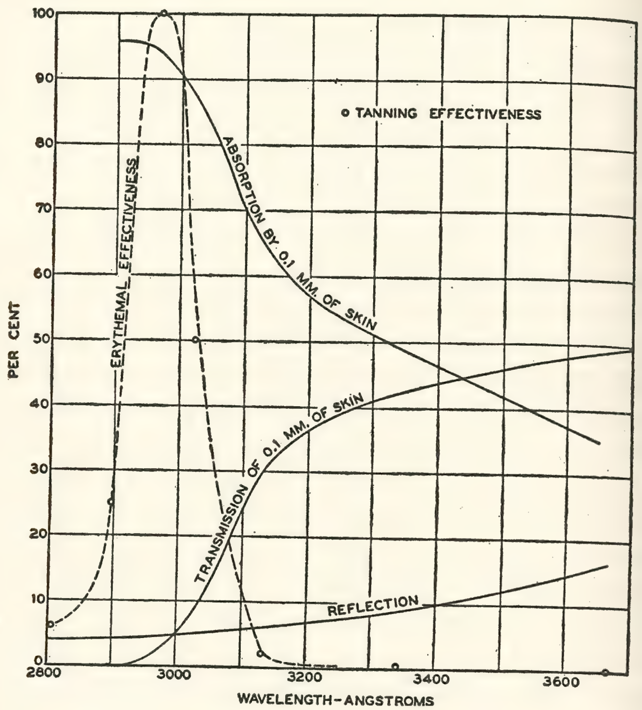


FIG. 31. Spectral characteristics of human skin. Owing to the difficulties involved these data provide only a qualitative view.

appears in a few days, with relatively little or no resultant tan. Consequently, it seems safe to assume that this short-wave energy does not reach a sufficient depth to affect appreciably the tanning process.

The characteristics of the tan produced by artificial sunlight are of considerable practical interest. In order to study this we exposed 12 representative subjects to a Type

S-4 sunlamp, having an energy distribution in the ultraviolet quite similar to that from the Type S-1 sunlamp which has been available for several years. As seen in Table XIII, the ultraviolet energy is confined principally

TABLE XIII

Distribution of Energy from Various Ultraviolet Sources Expressed in Microwatts per Sq. Cm.

λ	*Noon Sunlight July 12, 1938*	*D.C. Uviarc Mercury Arc*	*H-6 Mercury Quartz Jacket*	*S-1 Sunlamp*	*S-4 Sunlamp*
2400–2600. .		179	89	0	0
2600–2800. .		117	167	1.2	1.5
2800–2900. .		62	113	4.5	7
2900–3000. .	0.5	60	160	19	25
3000–3100. .	28	102	185	50	43
3100–3200. .	145	196	280	140	115
3200–3300. .	312	0	113	2	2
3300–3400. .	436	25	108	24	30
3400–3600. .	977	0	117	5	5
3600–3700. .	557	300	310	365	305

Artificial sources at 1 meter. Data for D.C. Uviarc and H-6 mercury sources from measurements by Dr. B. T. Barnes.

D.C. Uviarc: Common quartz mercury arc, 825 watts.
H-6 Mercury: High pressure quartz capillary arc, approximately 1000 watts.
S-1 Sunlamp: Mercury arc between tungsten electrodes in ultraviolet transmitting bulb, approximately 500 watts.
S-4 Sunlamp: High pressure quartz capillary mercury arc, with ultraviolet transmitting outer bulb, approximately 130 watts.

to λ2894, λ2967, λ3022, λ3130, λ3342 and λ3663, but the erythema and tanning are mostly due to λ2967, λ3022 and λ3130. Twelve small areas on the abdomen of each subject were exposed for periods of 2.5 to 10 minutes at a distance of 30 inches from the source of energy. The average exposure required to produce an MPE, when examined one day later, was 4 minutes. At the end of two months all except one subject still had some spots visible. The average exposure which produced a minimum perceptible tan (MPT) visible two months after exposure was 7.5 minutes.

Six months after exposure five of these subjects still had tanned spots visible, the average exposure corresponding to spots having an MPT rating being 7.5 minutes for these five, as compared with an exposure of 6.25 minutes for an MPT two months after exposure. These results indicate that twice an MPE exposure to this sunlamp produces a tan which will last two months or longer. This would correspond to a fairly strong erythema, although usually it would not be sufficient to cause a great deal of discomfort. Many users of sunlamps overlook the fact that they acquire a tan outdoors during a brief vacation only through successive sunburns. If they will keep a record of the number of sunburns and the total time of exposure to sunlight in acquiring a tan, they will find that some modern sunlamps successfully challenge the sun at its best. (See Plate III.)

We have also studied the effect of *sub-erythemal* exposures to an S-4 sunlamp in the production of tan. These exposures of untanned skin were made three times a week until a total of seven exposures were made. Twelve spots were exposed intermittently in this way for various lengths of time from 0.5 to 2 minutes and twelve other spots were given a single exposure five times as great as that of a single exposure of the corresponding spots of the former intermittent group. In other words, the spots receiving intermittent exposure were exposed for a total time which was 40 percent greater than the corresponding spots which received a single exposure. None of the spots receiving the intermittent exposure exhibited erythema or tan, while several of those which received the single exposure did develop erythema and tan. These results apparently indicate that if tanning is desired, the exposures should be long enough to produce some erythema, and this is probably true for sunlight. This is also interesting in connection with the work of Dr. H. J. Gerstenberger [22] with which we

were in close touch, which proved that sub-erythemal exposures or dosages of ultraviolet energy are sufficient to prevent and to cure rickets. Actually sufficient dosages

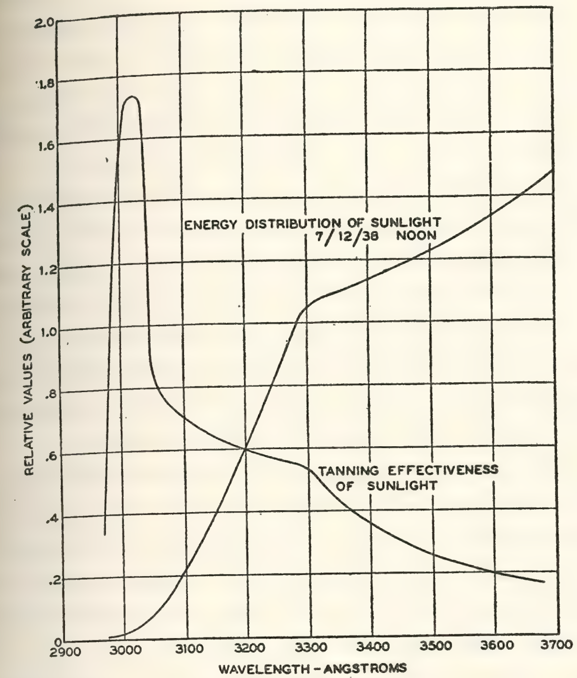


FIG. 32. The spectral distribution of ultraviolet energy in sunlight at noon on a clear July day and the relative tanning effectiveness of this energy of various wavelengths.

were found to be the daily exposures of the order of 0.1 to 0.25 of that required to produce a minimum perceptible erythema.

In Fig. 32 are shown the spectral distribution of energy in sunlight at noon on a clear day in July and the tanning effectiveness of energy in different parts of the spectrum. If it were desired to obtain a coat of tan without

appreciable erythema, it would appear to be necessary to screen off the energy from sunlight or a sunlamp shorter than approximately λ3300. This is the principle of the sun-tan lotions now on the market, as some of these which we have tested are highly absorptive of ultraviolet energy shorter than λ3300. Exposures to sunlight when using these lotions are necessarily quite long to result in tanning. They would also have to be much longer than those commonly made under an otherwise satisfactory sunlamp.

If an artificial source is to be used as a tanning lamp without causing appreciable erythema, it should produce very little energy shorter than λ3300 but a great deal of energy in the region λ3300–λ3800. The energy shorter than λ3300 can be absorbed by use of a suitable glass or other material. Table XIII shows the spectral distribution of radiant energy for noon sunlight in July compared with that from several sources of ultraviolet energy.

In our tests an exposure of 75 minutes, with the arc of an S-1 lamp focused upon the skin by means of a quartz lens through filter *G*, produced a moderate tan with little erythema. The energy density on the skin was 9 microwatts per sq. cm. for λ3342 and 6500 microwatts per sq. cm. for λ3663.

At a distance of one meter none of the artificial sources considered in Table XIII supplies more than about 5 percent of this value for energy at λ3663; hence they are not very practicable for the production of marked tan without initial erythema. Noon sunlight on a clear day in July in the spectral region λ3300–λ3800 would have about half the tanning effectiveness of the radiant energy which produced moderate tanning in our tests with filter *G* with an exposure of 75 minutes.

An artificial source requiring several hours' exposure would not make an acceptable tanning lamp unless the

exposure can be made while the subject is engaged in work or play. However, some sunlamps now available are practical sources for the production of tanning if the exposures are sufficient to produce a moderate erythema. Exposures of 5 to 10 minutes at a distance of two feet will accomplish this.

PROTECTIVE COATINGS FOR THE SKIN

It is a relatively easy matter to protect the skin from excessive erythemal exposures, for the reason that many materials absorb ultraviolet energy which is most effective in the production of erythema. In developing lotions and creams for this purpose, the chief problem is to produce something agreeable to the skin and to the user. The principle of socalled sun-tan preparations is to absorb much of the solar energy in the region of λ2900 to λ3100 or λ3200 and to transmit most of the tanning energy of longer wavelengths. This is made clear by Fig. 30 and the discussion pertaining to it.

Dry skin is generally less sensitive to erythemal energy than moist or wet skin. This fact is even evident in investigations involving untanned skin exposed under laboratory conditions in summer and in winter. A summary of our work on many subjects reveals that generally a measurably greater dosage is necessary to produce an MPE on untanned skin in winter than in summer. We have attributed this to the fact that the skin is more moist in the summer due to perspiration.

An effect of infrared energy seems to be indicated when it accompanies erythemal energy in considerable quantity. For example, the skin of the upper arm was exposed to the energy from an S-4 lamp with and without the addition of a high intensity of infrared energy from a filament lamp. The intensity of infrared energy was suffi-

cient for the skin to feel uncomfortably warm. It was found that a minimum perceptible erythema was caused in less time with the additional heating of the skin than without it. This work was done in the winter-time indoors under the condition of low humidity. Perspiration was not evident on the surface of the heated skin but it is probable that the skin below the surface was more moist with the additional heat than without it. Of course, there are other physical results of heating the skin that may also play a part.

Coatings for the protection of skin from excessive exposures to sunlight were found to be particularly desirable during the war. Many human beings suffered excessively from sunburn during long periods on life-rafts and in life-boats. There are other uses in everyday activities for coatings which effectively absorb the more effective erythemal energy. A few of the more practical results of an extensive series of tests may be of interest.[27]

In order to measure the spectral transmission of a thin film of specimens of protective material, a thin wedge was formed between quartz plates. In some cases it was quite difficult to obtain wedges free from air bubbles, which are more transparent than the material to be tested. Heating the quartz plates before applying the material generally made the material flow better. Since some of these materials diffuse the transmitted energy, it was advisable to grind the quartz plates on both sides and to make the transmission measurements with the quartz wedge placed in front of the slit of a quartz monochromator.

In order to provide a greatly accelerated test of the materials, the arc of a clear-bulb Type S-1 lamp, which emits no appreciable energy shorter than $\lambda 2800$, was projected by means of quartz lenses onto a ¼-inch hole in a sheet of thin metal. A quartz water-cell was placed in the

optical path to absorb much of the infrared energy in the beam. The erythemal energy passing through the hole was measured and found to be 60 times that of the highest intensity of erythemal energy in sunlight and skylight measured in Cleveland during the preceding several years. Thus an exposure of one minute to this intense erythemal energy was equivalent to one hour of the most intense natural sunlight available. This was computed to be sufficient to produce a minimum perceptible erythema on average untanned skin in approximately 8 seconds. The unprotected untanned skin of several subjects was exposed for 15 seconds to this intensity. All developed some erythema from the exposure and most of them appreciably more than the minimum perceptible, thus confirming the energy measurement.

To provide the maximum protection it is desirable to have the protective coating so opaque to energy in the erythemal region of the spectrum that a thin coating will provide complete protection over many hours of continuous exposure to tropical sunlight. Most of our erythemal tests have been made with thin coatings, though some tests were made with thicker coatings, all on the upper arms of the subjects. A thin coating is that which remains on the skin after the material has been fairly well rubbed in. Some promising materials apparently evaporate or are absorbed so that their usefulness is diminished.

Some petroleum jellies used alone were found to be very effective and their ability to absorb erythemal energy seemed to increase with the depth of color. Probably this is not true of all petroleum jellies, but apparently color is generally a means of appraisal. This fact is exemplified by the data in Table XIV.

TABLE XIV

Transmission-Factors, Expressed in Percent, of Five Different Petroleum Jellies and Mixtures of Materials for Ultraviolet Energy of Various Wavelengths. Thickness of Coating Is Indicated in Each Case

Specimen	*λ2967*	*λ3022*	*λ3130*	*λ3342*	*λ3650*
Petroleum jellies					
Colorless, .03 mm.	65	69	71	88	91
Very light amber, .03 mm.	32	32	55	88	94
Medium amber, .03 mm.	25	30	44	74	89
Dark amber, .03 mm.	5	9	21	52	75
Orange-red, .03 mm.	0	0	2	16	58
Mixtures of materials					
Mixture D, .03 mm.	0	0	0	1	3
Mixture J, .03 mm.	0	0	0	3	29
Mixture J, .06 mm.	0	0	0	0.3	7
Mixture L, .03 mm.	0	0	0.1	6	44
Mixture L, .06 mm.	0	0	0	0	0.3

Many mixtures of materials were tested. Measurements of transmitted energy and also the erythemal tests reveal zinc oxide and phenyl salicylate to be suitable absorbing agents. Some of the better mixtures tested had the following compositions:

Mixture D: Zinc oxide 10; phenyl salicylate 3; and petrolatum flava Q.S. 30.
Mixture J: Phenyl salicylate 10; petrolatum Q.S. 15.
Mixture L: Phenyl salicylate 10; zinc oxide 15; petrolatum flava 30.

All these mixtures would be improved in effectiveness, but not in appearance, by the use of the orange-red petroleum jelly listed in Table XIV. Many other cheap materials could be used if the appearance of the mixture, and of the user, were of no consequence. For example, powdered iron ore mixed with red petroleum jelly should provide a very inexpensive and highly protective coating. Of course, in all cases the mixture should not harm the skin and it should adhere reasonably well to the skin.

In testing the various materials and mixtures, untanned skin of the upper arm was exposed for 15 seconds without any coating. In all cases this exposure produced an erythema well above an MPE. The intense image of the arc which was used provided an erythemal exposure in one minute equivalent to one hour of the most intense sunlight in the vicinity of Cleveland during midday in midsummer. The exposures of the skin with the coatings applied were for 15 minutes, which was equivalent to 15 hours of exposure to the most intense sunlight near Cleveland. Average tropical sunlight at sea-level throughout a day is less effective erythemally than midday midsummer sunlight at 40° N. latitude. Such mixtures as D, J and L, and also the reddish petroleum jelly, applied to the skin, even in thin coatings, should protect untanned skin from excessive erythema or sunburn even if the exposure to sunlight continues day after day. In none of the 15-minute exposures (equivalent to 15 hours of intense sunlight) did a severe erythema develop on any of the subjects. In some cases there was no erythema and in others only a moderate erythema.

The foregoing discussion has been confined to protective coatings for emergencies and unavoidably long exposures to intense sunlight. For everyday use there are many lotions and creams which are satisfactory for obtaining a tan without excessive sunburn. It is a relatively simple matter to develop such preparations for the reason that most materials absorb ultraviolet energy more and more as the wavelength decreases from the short-wave end of the visible spectrum to the limit of the solar spectrum. It is also easy to test the efficacy of a given preparation by actual exposure of coated and uncoated areas of untanned skin to summer sunlight and skylight.

Units and Terminology for Biological Effectiveness

THE BIOLOGICAL effectiveness of ultraviolet energy has been widely and extensively studied and is being increasingly utilized, but the important foundation of physical science and the terminology are generally crude and, at best, empirical. The output of ultraviolet energy between certain wavelength limits may be determined for any source in terms of available units of energy or power. However, the measurement of biological efficiency by a physical method requires weighting the radiant energy of each wavelength with its corresponding biological effectiveness. From the viewpoint of physics, the procedure is quite simple, but spectral data pertaining to the biological effectiveness of ultraviolet energy are almost entirely lacking excepting for a few major initial or direct effects. This absence of spectral data emphasizes the need for physical standards and units, and for simplified terminology, which properly relate physical measurements of energy of various wavelengths with their biological effectiveness. Obviously, it is impossible to complete a system of units, terms and standards [28] without having available the necessary spectral data from the biological realm. Progress is inevitably concerned with these objectives, theoretical as they may appear to many practitioners at the present time. Therefore, the present discussion aims to suggest some of the necessary terminology by constructing analogies between the luminous effect and biological effects of radiant energy.

The methods of rating sources and dosages of biologically-effective radiant energy for various photochemical,

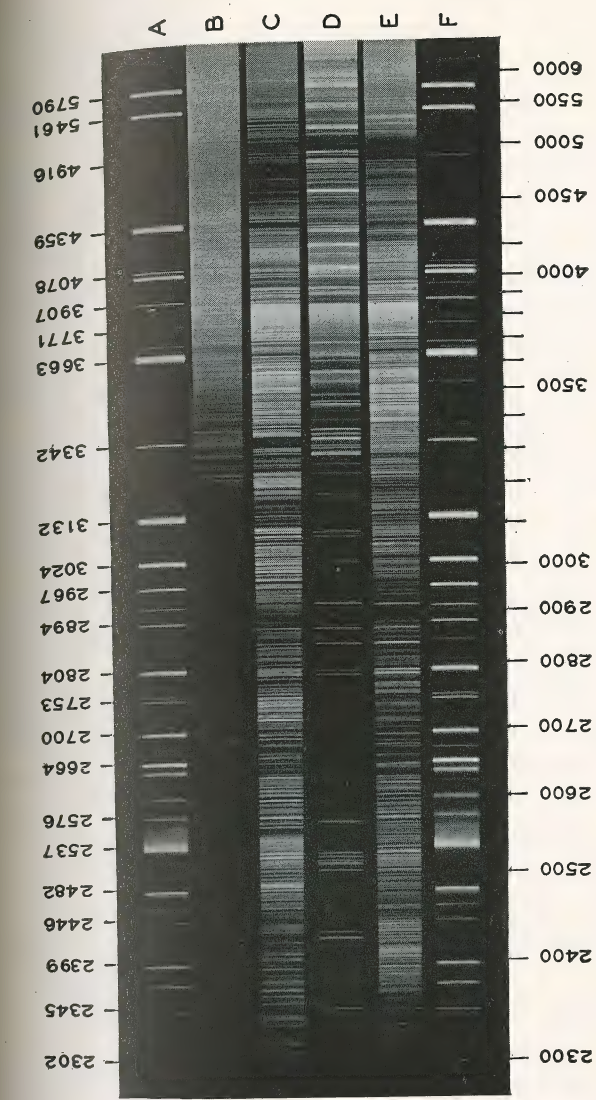


PLATE IV. Spectrograms of energy emitted by carbon-arcs.
A. Quartz mercury-arc
B. Eveready sunshine carbons
C. Eveready C carbons
D. Eveready E carbons
E. Eveready K carbons
F. Quartz mercury-arc

biological, therapeutic and prophylactic purposes are at present generally empirical. Perhaps none of the methods is entirely satisfactory, and some of them are quite indefensible from the broader view of physics which commonly has not been adequately considered or understood, and which must supply the scientific foundation for practice. Particularly in the cure of disorders and the maintenance of health, practice has demanded some kind of method of appraisal of sources and dosages before adequate knowledge of the physics of the subject and suitable measuring devices were available for developing a really scientific terminology and procedure.

The chief difficulty in accurately appraising sources of radiant energy for nearly all the many different biological, therapeutic and prophylactic uses is the lack of complete data pertaining to the effectiveness of radiant energy of various wavelengths. Among the uncounted results of ordinary radiant energy are erythema, tan, hyperemia, cure of rickets, prevention of rickets, killing of germs, production of Vitamin D and heating bodily tissue at various depths. Spectral data pertaining to effectiveness are available for some of these results, as indicated in Fig. 26. For some of the many uses, the most effective spectral range of energy and sometimes the most effective wavelength of energy are approximately known. Spectral data are most complete for germicidal and erythemal effects. The latter is an inescapable by-product of the exposure of human beings and various animals to ultraviolet energy and is readily measurable.

Viewed broadly, the visual sense is merely one of uncounted utilizers of radiant energy, but is a very generally important one to human beings. The term *lumen* has been coined to express light or *luminous flux* which visible energy produces in cooperation with the visual sense. The

light or luminous flux supplied by any specific source of visible energy is determined by multiplying the spectral distribution of energy by the spectral luminosity of radiant energy for each wavelength throughout the visible spectrum. The magnitude of the lumen is defined arbitrarily as all fundamental units are. The same procedure provides a basic scientific method of appraisal of sources and dosages of radiant energy for any physical, photochemical, biological, therapeutic or prophylactic use or effect. Each effect has its own spectral curve of effectiveness and only a few of these are even approximately established.

A UNIVERSAL ANALOGY

The evolution of terminology for light and lighting has given birth to some terms which may not be necessary at present, or at least may not be as logical as could be desired in the present state of the science of light production and of the practice of light utilization. In basing the present discussion upon the analogy mentioned, there is danger of extending some of the undesirable features of nomenclature and standards into a new field. On the other hand, the extensive experience with light and lighting is particularly valuable in clarifying the objectives pertaining to radiant energy and biological effect. The suggestions made herein make no pretense of completeness or finality but when first made [28, 29] they constituted an initial attempt to dissipate some of the confusion and unwieldiness of necessarily complex phrases.

The lumen is the unit of luminous flux and it is defined as the luminous flux emitted in a unit solid angle (a steradian) from a uniform point-source of one candle. There is a total of 4π unit solid angles and, therefore, the uniform point-source emits a total of 4π lumens. Similarly, for a given biological effect, we may define the unit of

biologically-effective flux emitted in a unit solid angle by an imaginary uniform unit point-source of this biologically-effective energy. We may term this analogue of the lumen a *viton*. The unit source of this biologically-effective energy emits a total of 4π vitons. A few salient characteristics of such a unit are presented in Table XV.

TABLE XV

A Far-Reaching Analogy Between Light or Luminosity and Any Biological Effect of Radiant Energy

	Pertaining to Visible Energy	*Pertaining to Ultraviolet Energy*
Unit	Lumen	Viton (for example)
Quantity	Luminous flux	Biologically-effective flux
Combining . . .	a. Spectral sensitivity of the eye and b. Spectral distribution of visible energy	a. Spectral biological effectiveness and b. Spectral distribution of ultraviolet energy
Result	Spectral distribution of luminosity (Integrated = Lumens)	Spectral distribution of a specific biological effectiveness (Integrated = Vitons)

There are many effects of radiant energy and certainly some of the "spectral curves of effectiveness" differ markedly among themselves as indicated in Fig. 26 and elsewhere. In fact, there is no reason to expect that any two of them are identical excepting, for example, those physiological effects that may be the result of the same direct effect of ultraviolet energy such as the production of Vitamin D and the prevention and cure of rickets. Some of these biological effects of ultraviolet energy which are of great interest to the health of human beings at the present time seem to be confined chiefly to ultraviolet energy shorter than $\lambda 3200$. Fundamental units must take into account the spectral ranges which are effective or utilized. The long-wave limits of biological effectiveness of ultraviolet energy are known approximately for germicidal, erythemal and antirachitic effects. The short-wave limits

are less well defined. The spectral effectiveness of energy in the production of erythema (minimum perceptible) upon average untanned human skin is now fairly well established as illustrated in Fig. 30 and Table X. For this

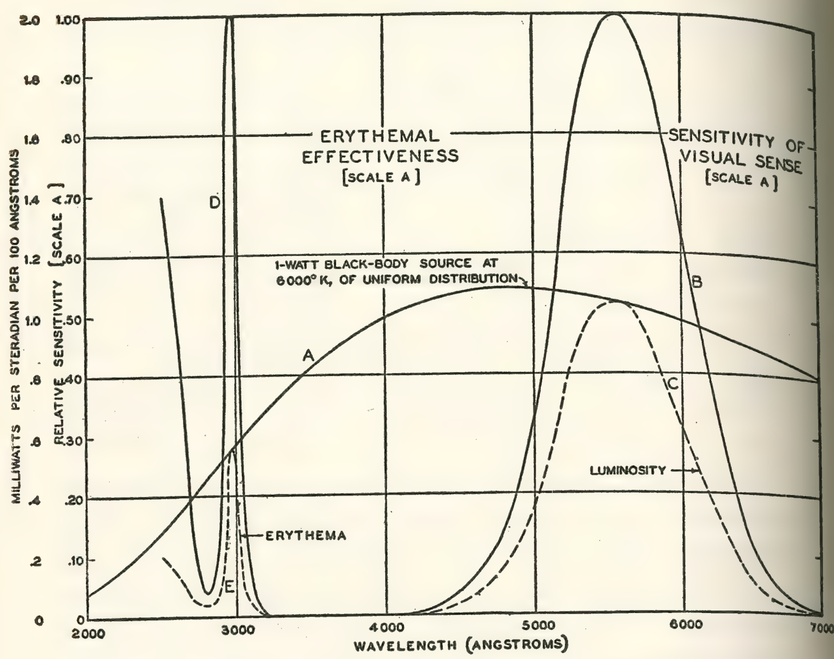


Fig. 33. A view of the analogy of the actions of visible energy upon the receiving visual sense and of ultraviolet energy upon the receiving untanned human skin.

reason this biological effect has been chosen for the purpose of illustrating the analogy which in turn reveals a logical system of units and terms for any biological effect of radiant energy.

In Fig. 33 is provided a view of the analogy of actions of visible energy upon the receiving visual sense and of ultraviolet energy upon the receiving untanned human skin. The result in one case is luminosity and in the other the

result is erythema. Curve *A* shows the spectral distribution of energy from a theoretical 1-watt black-body at 6000° K. which radiates energy uniformly in all directions. *B* is the luminosity curve which shows the luminous effect of equal amounts of radiant energy or the spectral sensitivity of the visual sense. When visible energy is properly weighted throughout the proper spectral range by applying the factors in *B* to the corresponding factors in *A*, the spectral luminosity curve *C* is obtained for this particular source of visible energy. This weighting converts visible or luminous energy into luminous flux. The area under *C* is proportional to the luminous flux.

Similarly, *D* in Fig. 33 is the erythemal curve of radiant energy, as shown in Fig. 30, or the spectral sensitivity of untanned white skin in the development of erythema. Curve *E* represents the specific biological (erythema-producing) effectiveness of ultraviolet energy produced by multiplying each value in *D* by the value in *A* for the corresponding wavelength. The area under *E* is proportional to the erythemal flux. If we had chosen the antirachitic effectiveness for *D*, the area under the resulting *E* would have been proportioned to the antirachitic flux. Similarly, if we had chosen the germicidal effectiveness for *D*, the area under the resulting *E* would have been proportional to the germicidal flux. This principle of weighting the energy of each wavelength by the effectiveness of energy of each corresponding wavelength can and must be applied to every specific biological effect. It is now obvious why spectral data pertaining to radiant energy and its biological effectiveness are so basically important.

ESSENTIAL UNITS AND TERMS

If a 1-watt black-body at 6000° K. were adopted as a unit source of biologically-effective ultraviolet energy, it

would emit 4π *vitons;* and each viton of erythemal flux would correspond to about 0.9 milliwatt of weighted integral power. That is, the mechanical equivalent of a viton of erythemal energy would be 0.0009 watt. This value would in general differ from that for another biological effect. (A watt = 1000 milliwatts = 1,000,000 microwatts.) The weighted light-producing power per steradian of the 1-watt black-body at 6000° K. is the area under *C* in Fig. 33 and is equal to about 10.9 milliwatts. Assuming the mechanical equivalent of light to be 1.61 milliwatts per lumen, the luminous intensity of this source is 6.75 lumens per steradian or unit solid angle.

A theoretical standard source which emits a unit of biologically-effective flux per steradian, or a total of 4π vitons, might be termed a *radion.* If we would arbitrarily confine our considerations to the application of ultraviolet energy, the theoretical standard source might be termed a *uvion.* However, the term radion is applicable to any biological effect of radiant energy, such as that of visible energy in the development of chlorophyl in plants. Of course, we might turn to mythology and adopt such a term as *Hyperion* after the father of Helios. Such a theoretical standard source provides a scientific foundation-stone rather than a unit for practical use. Therefore, a name for it is more of a theoretical than a practical necessity. For example, the candle as a unit of luminous intensity has relatively little practical use since the advent of the lumen.

From the analogy between visible and biologically-effective energy, a name might be given to the unit of biological flux per unit area. This unit intensity of biological flux upon a surface would be analogous to the footcandle which is equivalent to a lumen per square foot. A strict analogy is a viton per square foot. The utility of such a unit is obvious, and a short name for it is desirable.

There is no need for carrying the analogy to the footcandle as far as a foot-radion, a foot-uvion, or a foot-hyperion. It seems desirable to take advantage of the opportunity available and adopt such a name as *Finsen* in honor of a recognized pioneer in the biological use of radiant energy. Therefore, a finsen would be equivalent to one viton per unit area. At this point it is easy to adopt the metric system and define a finsen as a viton per sq. cm.

The unit for diffusely reflected or transmitted biologically-effective energy would be a viton per unit area or per sq. cm. At the present time it seems unlikely that such a term, analogous to brightness in the terminology of lighting practice, would be of much practical use.

The luminous efficiency of a source of visible energy is expressed in lumens per watt. Similarly the efficiency of a source as measured by a specific biological effect would be expressed in vitons per watt. Of course, as previously stated, the viton would be a specific one applying to the particular biological effect. In the case of erythemal effect it would be an erythemal viton or E-viton.

The lumen-hour has little application outside the realm of cost of lighting. However, in applications of biologically-active energy, time or duration of exposure is a very important factor in dosage and other usage. In fact, the viton-hour would be analogous to milligrams of cod-liver oil, for example, in dealing with antirachitic effect.

In these proposals the finsen is an analogue of the footcandle. Therefore, finsen-hours are analogous to footcandle-hours. In order to utilize a finsen-hour as a measure of dosage it must be multiplied by area of exposed surface. Finsen-hours times the area of the receiving surface in square centimeters yield viton-hours.

SPECIFIC TERMS FOR ERYTHEMAL EFFECTIVENESS

From the foregoing it is seen that an entire system of units and terms can be developed for biological effectiveness of radiant energy just as one has been developed through necessity for the specific effect of visible energy which produces light or luminosity. However, it is emphasized that various biological effects differ quantitatively in their relation to radiant energy of various wavelengths. Therefore, specific units and terms must be developed for each specific biological effect. To illustrate this fact the general analogy is now presented as a specific one dealing with erythemal energy, its production and use.[29] For this purpose we might have chosen germicidal energy for, as discussed in other chapters, the germicidal effectiveness of energy of various wavelengths is now fairly well established for the killing of B. coli. It differs in degree for various organisms. Other biological effects are not established well enough for this purpose. Although erythemal effectiveness is not necessarily a measure of any other biological effect, it is of great importance in many present and some promising future applications of ultraviolet energy.

Erythemal Energy is radiant energy *capable of producing erythema*, just as visible radiant energy is capable of producing luminosity or the sensation of brightness. It is measured in energy units.

Erythemal Flux is analogous to luminous flux or light in the strictest sense of the term. Erythemal flux is *erythemal energy weighted* according to the effectiveness of equal amounts of energy of various wavelengths in producing erythema. Luminous flux is visible energy weighted according to the effectiveness of equal amounts of visible energy of various wavelengths in producing the sensation

of brightness or luminosity. Erythemal flux is radiant energy weighted according to Figs. 30 and 33 and Table X. Erythemal flux in microwatts, for example, integrated throughout the erythemal spectrum is equivalent in the production of erythema to the same number of microwatts of radiant energy of maximum erythemal effectiveness.

For sunlight and ultraviolet energy from artificial sources for general use as substitutes for sunlight, the erythemal energy is confined chiefly to the energy longer than λ2900. This is also true for carbon and quartz mercury arcs when properly filtered for this purpose. However, these fundamental units and terms are applicable to any source or equipment.

UNIT OF ERYTHEMAL FLUX OR E-VITON

This is analogous to the lumen. For general use an erythemal viton may be designated as an E-viton. A germicidal viton may be designated as a G-viton and so on. Such a procedure was contemplated in the original discussion of terminology by the author and one of his colleagues, L. L. Holladay.[28, 29] The E-viton has been standardized by the Illuminating Engineering Society and the International Commission on Illumination as a term and also as a quantity equal to 10 microwatts of erythemal flux. This means 10 microwatts after being erythemally weighted and, of course, is equivalent to 10 microwatts of erythemal energy of the wavelength of maximal erythemal effectiveness.

By computation it is found that a 1-watt black-body source operating at about 3255° K. emits one E-viton in every steradian, or unit solid angle, which means a total of 4π or 12.57 E-vitons. At temperatures of 4200° K. and 6480° K., the total outputs of a 1-watt black-body are, respectively, 125.7 and 1257 E-vitons. Mazda CX lamps have tungsten filaments in special ultraviolet-transmitting

bulbs. A 60-watt CX lamp emits a total of 140 E-vitons and a 500-watt CX lamp emits 3200 E-vitons. The more powerful sources of ultraviolet energy emit much more erythemal flux. For example, the 440-watt S-1 lamp emits about 70,000 E-vitons.

UNIT INTENSITY OF ERYTHEMAL FLUX

This is the analogue of the footcandle or, more properly, the phot. It would be one E-viton per sq. cm. A name for this term is needed and we have suggested *finsen* in honor of a recognized pioneer in therapeutic applications of ultraviolet energy. According to the magnitude of the E-viton, a finsen is 10 microwatts of erythemal flux incident upon a projected area of one centimeter. Of course, if the finsen were similarly used for other effects, the unit for intensity of erythemal flux would be designated as an E-finsen.

Average untanned skin must be exposed about 20 minutes to midsummer sunlight at sea-level on a clear day at noon in order to obtain a minimum perceptible erythema (MPE). The intensity of erythemal flux in this case is about 18 microwatts per sq. cm. or 1.8 finsens or 1.8 E-vitons per sq. cm.

UNIT INTENSITY OF EXPOSURE

This unit logically becomes one finsen for one second or one finsen-second. In accordance with the magnitude of the E-viton, the unit of dosage or exposure is 10 microwatt-seconds per sq. cm. or 100 ergs of erythemal flux per sq. cm. It is obviously convenient to reduce these phrases to their equivalent of one finsen-second. This might be abbreviated to one FS. A finsen-minute would be one FM and a finsen-hour would be one FH. Various measurements and computations indicate that about 250,000 ergs

of erythemal flux per sq. cm. are necessary to produce an MPE (minimum perceptible erythema) on average untanned skin. This is equivalent to about 2500 finsen-seconds or 42 finsen-minutes or 0.7 finsen-hour. Naturally it is equivalent to 42 E-viton-minutes per sq. cm. Thus about 40 E-viton-minutes per sq. cm. produce an MPE on average untanned skin.

UNIT OF DOSAGE

This is the result of an exposure to one E-viton for one second or one E-viton-second. This unit of exposure is equivalent to 10 microwatt-seconds, or 100 ergs, of erythemal flux. When the intensity of exposure is known, the total dosage in E-viton-seconds is obtained by multiplying the intensity of exposure in finsen-seconds by the exposed area of the receiving surface in square centimeters. The unit of area is one sq. cm. Therefore, the unit of dosage is one E-viton-second per sq. cm. multiplied by one sq. cm. or one E-viton-second. If the total area exposed is X sq. cm., the total dosage equals X E-viton-seconds.

In the prevention and cure of rickets the area of exposed skin is a factor, although its relationship to the final results is not known with accuracy. From a series of experiments on the cure of rickets in children by Dr. H. J. Gerstenberger and colleagues for the purpose of establishing the threshold dosage, the results indicate that about 12 percent of an MPE exposure daily cures severe rickets in babies almost fully clothed or with projected skin areas of about 500 sq. cm. This corresponds to about 150,000 E-viton-seconds per day or 42 E-viton-hours per day. Possibly even smaller dosages will be found effective and at least it may be established eventually that specific exposures need not be applied every day. If this is true, the total

effective dosage may be less than the present summary of daily exposures.

EFFICIENCY OF SOURCE

Luminous efficiency is expressed in lumens per watt. Any source of biologically-effective radiation can be rated in vitons per watt. Erythemal efficiency of a source would be expressed in E-vitons per watt.

In Table XVI is presented a brief summary of erythemal units, terms and magnitudes developed in the present paper, not only because they are needed or are useful, but also because they illustrate a procedure sorely needed in connection with other biological effects of radiant energy. The same system of units and terms is desirable for any other effect of radiant energy. These units and terms can be given quantitative values only when adequate data relating radiant energy and the specific effect are available.

TABLE XVI

Summary of Erythemal Units and Terminology

Unit	*Name*	*Magnitude*
Unit erythemal flux	E-viton	10 microwatts of erythemal flux
Unit erythemal source	(Radion)	4π E-vitons emitted
Unit intensity of erythemal flux	Finsen	One E-viton per sq. cm.
Unit intensity of erythemal exposure	Finsen-second	One E-viton per sq. cm. for one second
Unit erythemal exposure or dosage	E-viton-second	One E-viton for one second
Erythemal efficiency of source	E-vitons per watt	One E-viton per watt

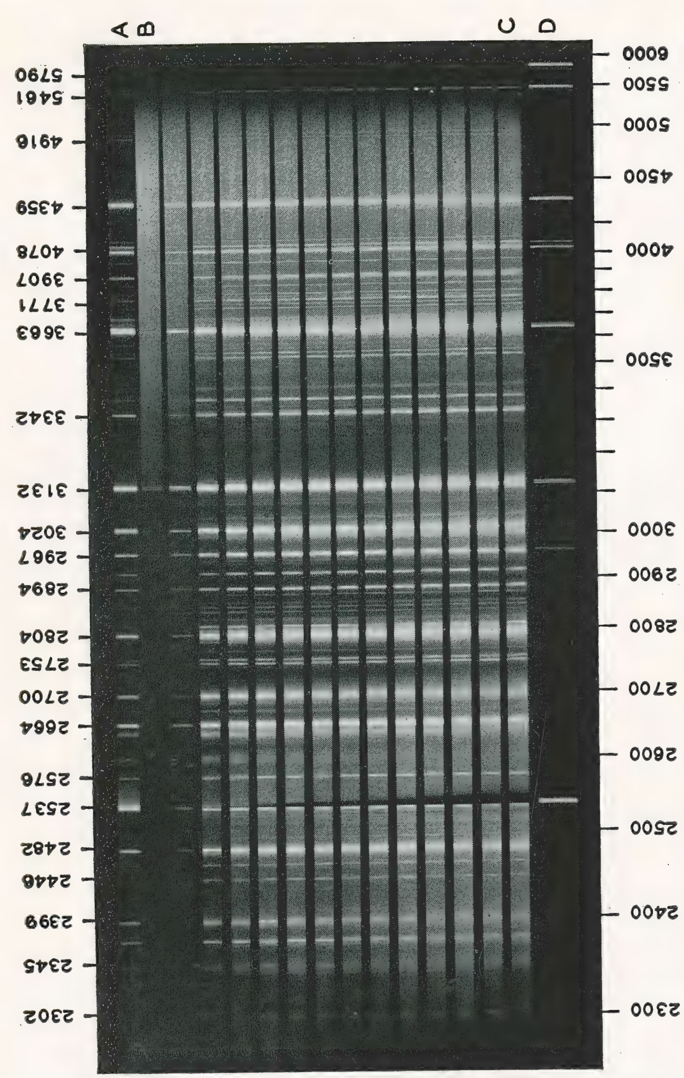


PLATE V. A series of emission spectra of a tungsten-mercury S-1 lamp with quartz bulb. *B* was made 10 seconds after starting and *C* 30 minutes later. Note absorption-band appearing at λ2537 as density and pressure of mercury vapor increases due to increasing temperature. *D* is emission spectrum of low-pressure (germicidal) mercury lamp. *A* is spectrum of common quartz mercury-arc.

Germicidal Energy

NOT LONG after the discovery of the existence of microorganisms, known in general as bacteria, it began to be observed that sunlight killed at least some of them. After the discovery of ultraviolet energy in 1801, this invisible energy was suspected of being lethal to organisms that are not too well protected with an outer covering that cannot be penetrated or damaged by ultraviolet energy. During the present century an increasing amount of research has been devoted to the problem of ascertaining the germicidal effectiveness of ultraviolet energy of various wavelengths.

It is now generally accepted as a fact that nearly all bacteria may be killed or attenuated by ultraviolet energy of certain wavelengths but that different species vary considerably in their resistivity or rate of destruction. Those organisms whose normal habitat is the animal body are generally more easily killed than those living in an environment flooded with sunlight or skylight. It is natural that the latter become more or less adapted to solar energy, including the ultraviolet component of sunlight and skylight.

WAVELENGTH OF MAXIMAL EFFECTIVENESS

A number of investigations have been made of the relative germicidal effectiveness of ultraviolet energy between λ2200 and λ3000. The results generally indicate that the maximum effectiveness occurs somewhere between λ2500 and λ2650. Hollaender[30] found that the relative effectiveness of ultraviolet energy of various wavelengths was approximately the same for different types of bacteria.

However, it is known that the resistivity of various types of bacteria varies considerably. Gates[31] obtained some results which indicated that the wavelength of maximum germicidal effectiveness varies somewhat with the percent of bacteria killed. He found this maximum to be at λ2537 for S. aureus and λ2650 for B. coli with λ2537 nearly as effective. Hollaender and Claus[32] found energy of λ2537 to be most effective for B. coli but stated that there were indications that the maximally effective energy was between λ2537 and λ2650. Some earlier work by L. L. Holladay indicated that the maximal germicidal effectiveness of radiant energy in killing B. coli on agar plates is somewhere in the region between λ2537 and λ2576. I. Weinstein[33] presented data showing that energy of λ2650 was most effective in killing paramecia, but energy of λ2537 was very nearly so. An extensive investigation recently completed by the author and his colleagues definitely indicates that the maximal germicidal effectiveness in the killing of B. coli in shallow depths of water is exhibited by energy from λ2537 to λ2575. Within the experimental error, any wavelength in this spectral range may be accepted as that of maximal effectiveness.

SPECTRAL RANGE OF GERMICIDAL EFFECTIVENESS

Doubtless the spectral range of germicidal effectiveness, particularly the short-wave limit, is determined by the ability of the energy to penetrate the organism sufficiently to produce enough damage to kill it. The transparency of substances is generally low for short-wave ultraviolet energy, and in general the transmission-factor decreases with decreasing wavelength. Even air absorbs ultraviolet energy markedly beyond λ2000. It is conceivable, and even probable, that short-wave ultraviolet energy cannot penetrate the outer coating of some organisms sufficiently to produce enough damage to kill them.

The short-wave limit of germicidal effectiveness, as announced by various investigators for B. coli and similarly susceptible bacteria, ranges from λ1700 to λ2260. It is probable that these variations are due largely to different intensities of energy and experimental conditions.

It is well known that the germicidal effectiveness of ultraviolet energy decreases rapidly as the wavelength increases from λ2537 to the short-wave limit of the solar spectrum in the region of λ2930. Since the germicidal effectiveness of energy of longer wavelengths than λ3100 is relatively low, little work has been done on the relative effectiveness of energy in the solar spectrum. Hollaender[30] states that the intensity of energy or exposure necessary to kill bacteria with energy of longer wavelengths than λ3650 is 1000 to 10,000 times that necessary with energy shorter than λ3000. Coblentz and Fulton[34] have presented some data for long-wave ultraviolet energy.

There is little doubt that the long-wave limit of germicidal effectiveness may depend somewhat upon the type of organism, but particularly upon the exposure and experimental techniques. As seen later, the author and his colleagues studied the germicidal effectiveness, with B. coli on agar and in shallow dishes of water to which nutrient had been added, by means of filters whose short-wave cut-offs or limits of transmission varied from λ2000 to λ5800. The exposures ranged from 0 to 210 minutes, depending upon the filter and the source of energy. Not only is the ultraviolet energy abiotic throughout the long-wave region, but visible energy kills B. coli in water if the exposure—intensity × time—is adequate. The germicidal effectiveness of λ2537 appeared to be 4000 times that of energy of λ3650; about 10,000 times that of λ4047; at

least 30,000 times that of λ5461; and perhaps 35,000 times that of λ5780.

SPECTRAL GERMICIDAL EFFECTIVENESS

There are various basic reasons for determining the germicidal effectiveness of radiant energy throughout the entire spectral range of ultraviolet and visible energy. Such data are essential to the development of the science upon which the technology of use of germicidal energy must be founded. With such data available, the germicidal efficiency of sunlight, skylight and artificial sources of germicidal energy can be determined. In many ways the spectral effectiveness of radiant energy is useful in practice. For these reasons the author and his colleagues, L. L. Holladay and A. H. Taylor, undertook an extensive series of researches whose combined results have established the effectiveness of radiant energy of various wavelengths in the killing of B. coli. The final results are presented in Fig. 34.

First the region between λ2220 and λ3132 was studied by means of a large quartz spectograph in which agar plates seeded with B. coli were exposed to the ultraviolet spectrum of a quartz mercury arc. The intensity of radiant energy of various wavelengths incident on the plate was determined. After exposure to the ultraviolet spectrum for various periods of time, the seeded plates were incubated for about 24 hours at 37° C. Then the colonies were actually counted on equivalent areas of exposed and unexposed portions of the plates. Exposures ranged from 1 to 60 minutes.

A second method involved exposures of B. coli in shallow dishes of water about one cm. in depth. In order that the bacteria around the edges of the dish might be more or less protected from the radiant energy and, as a

consequence, might re-infect the remainder of the solution, the horizontal dish of water was revolved by electric power at a rate of two revolutions per minute. Thus all parts of the dish were more nearly equally exposed.

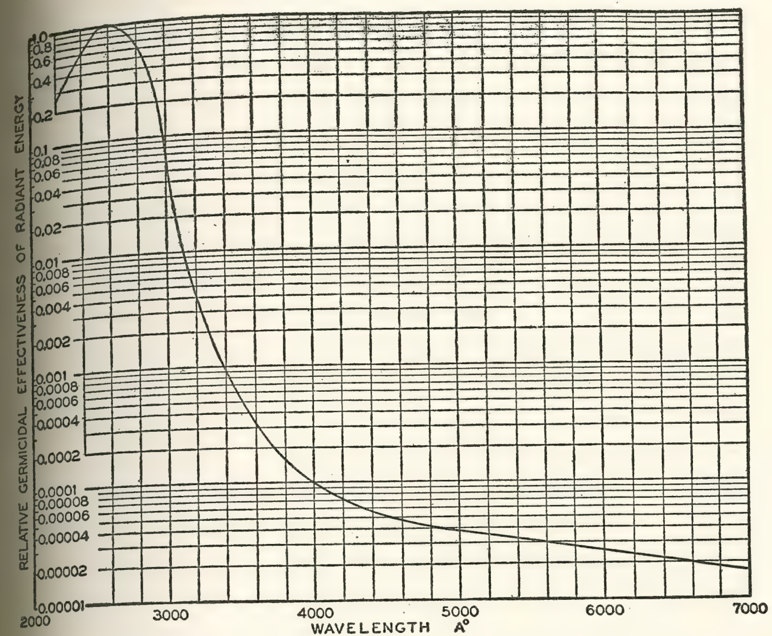


Fig. 34. The relative germicidal effectiveness of ultraviolet energy of various wavelengths as determined by the killing of B. coli on seeded agar plates and in shallow dishes of distilled water.

Precautions were taken to eliminate the tendency of the organisms to die from other influences than irradiation. The temperature of the water was kept from rising appreciably by ventilating the dish from above and below. The composition of the liquid was so adjusted by the addition of a minute quantity of heart infusion broth that the concentration of B. coli in the water remained sufficiently constant for hours if need be. At any rate this provided

effective control by comparing the exposed samples with those unexposed. The irradiated samples were kept in comparative darkness, along with the control samples, until all samples had been exposed. Then cultures were made from all the samples at the same time and under identical conditions. The B. coli were originally 24 hours old. The cultures were made by mixing a measured amount of each sample in a standard solution of Levine's eosin methyl blue agar. After incubating at 37° C. for 24 hours, the colonies were counted in the usual manner.

The work was done with combined sunlight and skylight and with skylight alone by casting a shadow of the sun on the dish. The spectral energy distribution of sunlight during the midday hours on clear days was determined as discussed in Chapter II. Exposures were made on many clear days and standard spectral energy distributions were used, as developed during many years by ourselves and others. A series of filters was used. Their short-wave limits of transmission and their transmission-factors for energy of various wavelengths are shown in Fig. 35. Brief descriptions and the approximate short-wave limit of transmission of the filters, designated by the letters in Fig. 35, are as follows:

A, Corning No. 974 glass	λ2000
B, Corning No. 970 glass	2600
C, Pyrex	2900
D, Blue fluorescing glass	3100
E, Ordinary plate glass, ½ inch	3300
F, Green glass	4000
G, Yellow glass	5000
H, Red glass	5800

The dishes were exposed to skylight and to combined sunlight and skylight on clear and fair days during the middle part of the day. An important reason for using B. coli in water was the necessity for long exposures for

long-wave ultraviolet energy and visible energy. The series of filters progressively absorbed more and more of the short-wave energy as shown in Fig. 35.

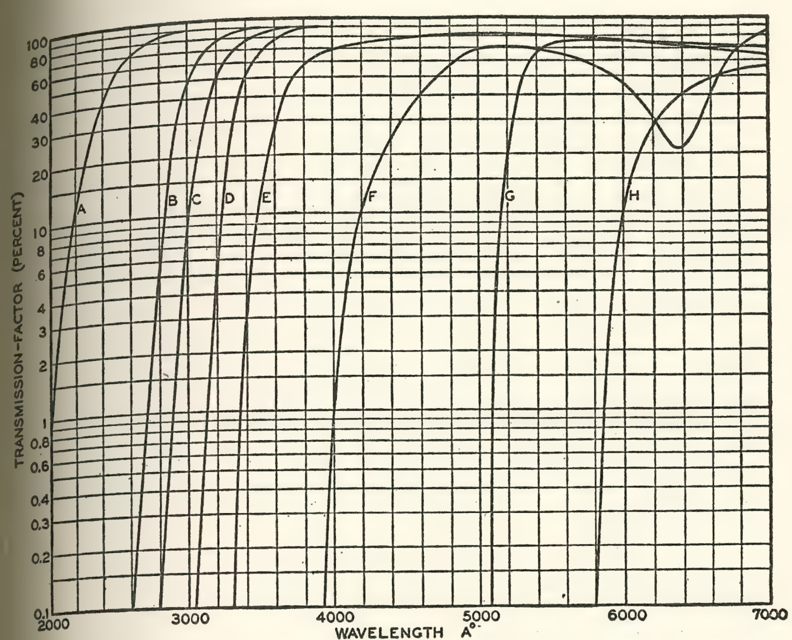


Fig. 35. The transmission-factors of a series of useful filters for ultraviolet and visible energy of various wavelengths.

A, Corning 974 glass	*E*, Ordinary plate glass
B, Corning 970 glass	*F*, Green glass
C, Pyrex	*G*, Yellow glass
D, Blue-fluorescing glass	*H*, Red glass

Finally, a 360-watt quartz mercury arc was used. The dishes containing the B. coli in water were exposed to radiant energy from this source at a distance of one meter through the various filters. By properly taking into account the energy of various wavelengths which reached the B. coli through each filter, it became possible to appraise

the germicidal effectiveness of equal amounts of energy for each of the wavelengths of energy in the spectrum of the quartz mercury arc. Thus data were obtained for energy from λ2259 to λ6830. These data were combined with the data obtained by the other two investigations into the over-all curve of spectral germicidal effectiveness illustrated in Fig. 34. We believe this well represents the facts for killing B. coli in air, on agar and in shallow depths of water.

The intensity of energy in the various spectral bands of the quartz mercury arc without a reflector is presented in Table XVII at a distance of one meter. The germicidal effectiveness of energy as determined for each wavelength is presented in the third column. In the last column is the intensity of germicidal flux of the various wavelengths at a distance of one meter. Germicidal flux is germicidal energy weighted in accordance with its germicidal effectiveness. It is described as equivalent microwatts per sq. cm. of energy of the wavelength of maximum germicidal effectiveness.

GERMICIDAL EFFECTIVENESS OF SUNLIGHT AND SKYLIGHT

In Fig. 36 are shown the survival-ratios of B. coli in shallow dishes of water after exposure to combined sunlight and skylight from the entire sky during the midday hours on clear days in summer. These data were obtained with no filter over the dish. On clear days the intensity of germicidal flux on the horizontal dish averaged about 5.7 microwatts per sq. cm. of energy equivalent to the germicidal effectiveness of λ2537. On hazy or slightly overcast days the intensity of germicidal flux was measurably less. An average value for midday on several days was 3.64 microwatts per sq. cm. equivalent to λ2537 in germicidal effectiveness.

TABLE XVII

Data Obtained on a Horizontal Surface One Meter Below a 360-Watt, 115-Volt, Quartz Mercury Arc without a Reflector

Wavelength in Angstroms	*Microwatts per Sq. Cm. at 1 Meter*	*Relative Germicidal Effectiveness*	*Equivalent Microwatts per Sq. Cm. of λ2537*
2259	10.4	.33	3.43
2353	12.3	.50	6.15
2399	5.8	.62	3.60
2446	4.3	.73	3.14
2483	12.0	.84	10.08
2537	35.5	1.00	35.50
2576	16.8	1.00	16.80
2654	28.3	.96	27.20
2700	6.7	.87	5.83
2753	4.1	.72	2.95
2804	11.8	.57	6.72
2894	7.3	.31	2.26
2925	2.5	.23	.57
2967	15.7	.13	2.04
3022	29.5	.045	1.33
3129	67.6	.008	.54
3341	14.6	.0013	.019
3654	94.8	.00023	.0218
4047	38.3	.00009	.0034
4358	55.7	.000058	.0032
5461	64.5	.000031	.0020
5780	62.2	.000028	.0017
6830	7.7	.000020	.0002
	608.4		128.1913

Relative Bactericidal Effectiveness of Radiant Energy

Wavelength in Angstroms	*Percent of Maximum*	*Wavelength in Angstroms*	*Percent of Maximum*
2200	25	2800	60
2300	40	2900	30
2400	63	3000	6
2500	91	3100	1.3
2537	100	3200	0.4
2575	100	3400	0.09
2600	99	3600	0.03
2700	87	4000	0.01

Visible energy from λ4000 to λ7000 varies between 0.01 and 0.001 percent, or one thousandth and one ten-thousandth, of the (maximal) effectiveness of energy of λ2537 to λ2600 as determined for B. coli.

By casting a shadow on the dish, the effectiveness of skylight from the entire sky was studied. The duration of these exposures varied from 0 to 210 minutes. The intensity

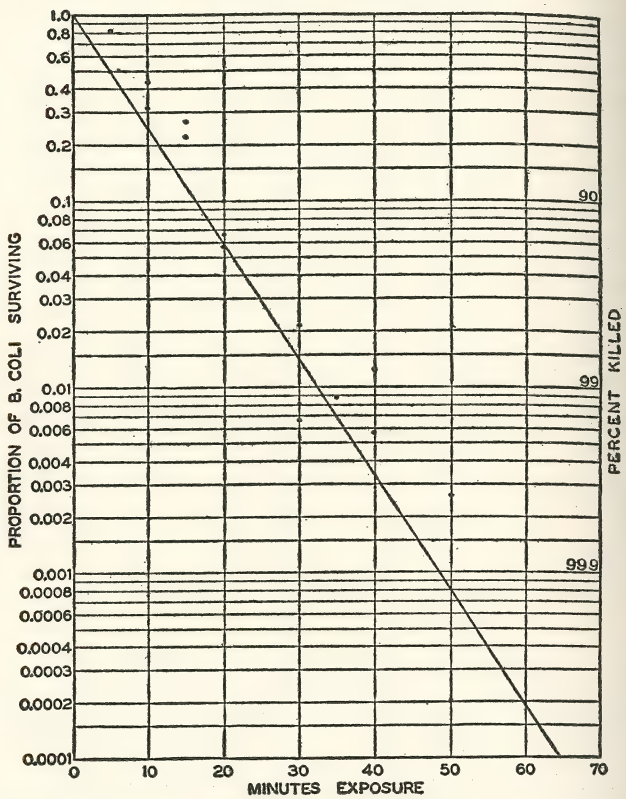


FIG. 36. Survival-ratios of B. coli in shallow dishes of water after various exposures of 0 to 60 minutes to combined sunlight and skylight from the entire sky during the midday hours on clear days in summer.

of germicidal flux on the dish averaged about 2 microwatts per sq. cm. of energy equivalent to λ2537 in germicidal effectiveness and it was approximately the same for sky conditions that may be described as clear, scattered clouds,

hazy and slightly overcast. During the midday hours on clear days the entire sky appears to contribute about 35 percent of the total germicidal flux from combined sunlight and skylight as measured on a horizontal plane. On hazy or slightly overcast days the entire sky contributes a greater percentage of the total germicidal flux due to combined sunlight and skylight. An average of a number of such days indicates that the entire sky contributed about 60 percent of the total.

The foregoing results for skylight might be anticipated from the data presented in Chapter II on the erythemal energy and flux in sunlight and skylight. However, the measurement of erythemal effectiveness of sunlight and skylight provides only an approximate indication of their germicidal effectiveness. The intensity of erythemal flux on a horizontal plane was found to be generally greater than the intensity of germicidal flux. An average of many measurements indicated that the former was generally from 2 to 5 times as great. This might be suspected from the fact that the maximal erythemal effectiveness is at λ2967 which is near the short-wave limit of the solar spectrum. The maximal germicidal effectiveness is in the region of λ2537 which is far beyond the limit of the spectrum of sunlight or skylight.

COMPARISON OF SOURCES

The survival-ratios of B. coli in shallow dishes of water are shown in Fig. 37 after exposure from 0 to 3 minutes to the radiant energy from a 360-watt, 115-volt quartz mercury arc one meter above the dish. The source was not equipped with a reflector. Naturally with a proper reflector the intensities would be greater but they would be dependent upon the characteristics of the reflector. The intensities of radiant energy in different spectral bands, incident on

the shallow dish, are presented in Table XVII. It is seen that at a distance of one meter this 360-watt quartz arc kills

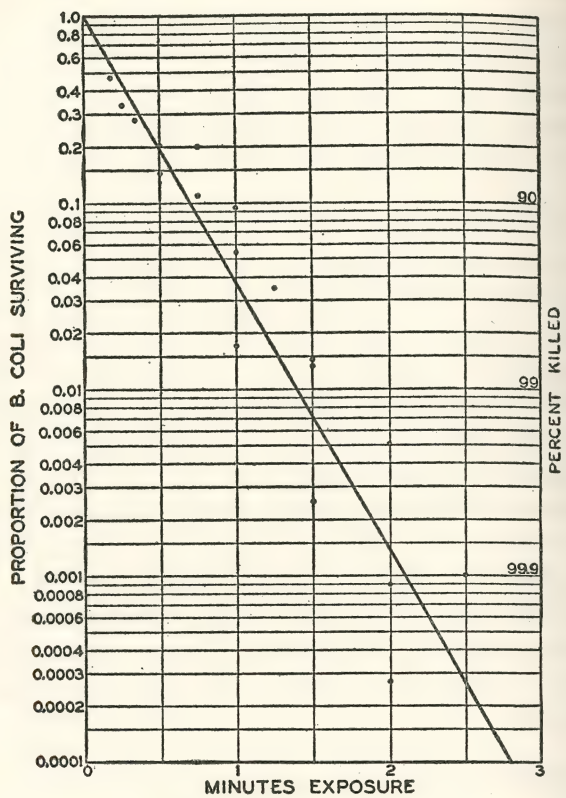


FIG. 37. Survival ratios of B. coli in shallow dishes of water after various exposures of 0 to 3 minutes to the radiant energy from a 360-watt quartz mercury-arc one meter above the dish.

as many B. coli in water as the midday intensity of combined sunlight and total skylight kills in one hour.

The data in Fig. 37 also represent fairly well the survival-ratios of B. coli in water after exposures of similar duration to a 30-watt germicidal lamp at such a distance

that the same intensity of germicidal flux is incident on the shallow dish. The significance of this is clear from Table XVIII. By following through the data the conclusion is reached that the germicidal efficiency (output of germi-

TABLE XVIII

Comparing the Germicidal Efficiencies of a 360-Watt, 115-Volt Quartz Mercury-Arc with a 30-Watt, 115-Volt Germicidal Lamp Which Is a Low-Pressure Mercury Arc in a Tube of Special Ultraviolet-Transmitting Glass

	Quartz Arc	*Germicidal Lamp*
Watts input		
Lamps	360	30
Ballast	60	9
Total	420	39
Watts output		
λ2200–2800	10.4	7.9
λ2800–3165	10.3	0.21
λ3165–3800	8.3	0.16
λ3800–7600	17.4	0.9
λ2200–7600	46.4	9.17
Watts output of germicidal flux		
λ2200–2800	8.74	7.9
λ2800–3165	1.03	
λ3165–3800	0.003	
λ3800–7600	0.001	
Microwatts of germicidal flux per sq. cm. at one meter (energy of λ2537 or its equivalent)	105	82
Relative germicidal flux per watt of total input	11.5	100

cidal flux per watt) of this 360-watt quartz mercury arc is about 11.5 percent of that of the socalled germicidal lamp. In other words, the latter is about nine times more efficient than the former for germicidal purposes. These data apply to the lamps without reflectors. Considering the low wattage of the germicidal lamps, the difficulties from the heating effect are negligible compared with those attending the use of the less efficient quartz mercury arcs. Therefore, germicidal lamps can be used closer to materials without damage

from heat. Taking all the practical aspects into account one may conclude conservatively that a 30-watt germicidal lamp can often be more effective in practice than a 300-watt quartz mercury arc.

In Table XVIII it is seen that the intensity of germicidal flux on a horizontal plane one meter below the germicidal lamp is 82 microwatts per sq. cm. This can be considerably increased by means of a reflector of properly treated aluminum. About a foot below a 30-watt germicidal lamp in a proper reflector one can readily obtain an intensity of germicidal flux of 600 microwatts per square centimeter. This intensity is 100 times that at the earth's surface due to combined sunlight and total skylight during midday on clear days in midsummer. It is 300 times that due to the entire sky. Therefore, from a practical viewpoint the germicidal effect of one 30-watt lamp can be easily as great in one minute as that of the best combined sunlight and skylight in one hour.

The foregoing data pertaining to quartz mercury arcs are subject to change due to various factors in the design and maintenance of the burners. The data for the 30-watt germicidal lamp are also subject to change if the composition and thickness of the ultraviolet-transmitting glass are altered. However, the comparisons of these various sources reveal the great advantage of the new germicidal lamps over the older quartz mercury arcs and the really enormous advantage over the best sunlight and skylight which reaches the earth's surface. The germicidal lamp is an overwhelming challenger of the sun. Comparing its possibilities in germicidal fields with that of its predecessor, the quartz mercury arc, is analogous to comparing the possibilities of modern fluorescent lamps in lighting with those of the old carbon-filament lamps.

The spectrum of the energy emitted by the germicidal lamp is shown at the bottom of Plate V. This is the spectrum of mercury vapor at a very low pressure. It is seen that there are many gaps in the spectrum compared with the spectrum of mercury at relatively high pressures. The top spectrogram on Plate V is that of the ordinary quartz mercury arc. The other spectrograms were obtained with an S-1 lamp in a quartz bulb. This lamp is a combination of mercury vapor and tungsten filament as illustrated in Fig. 6. These spectrograms were made successively, beginning immediately after the S-1 lamp was turned on and at various intervals afterward up to 30 minutes. It is seen that as the lamp became hotter, the spectrum of mercury became more pronounced. Also an absorption band became more and more evident in the region of λ2537. This shows how the pressure or density of mercury vapor alters the spectral character of the energy it emits. Incidentally, the S-1 lamp is equipped with a bulb of special glass with a short-wave cutoff at about λ2800. Plate V shows the spectral character of energy emitted when it is equipped with a quartz bulb.

A graphical summary [64] of the spectral distribution of energy emitted by three kinds of sources of ultraviolet energy is found in Fig. 38. Some of the major effects of light and radiant energy are also shown in order to illustrate the relative values of the sources producing a certain effect. It is seen that the quartz mercury-arc emits ultraviolet energy in various regions of the ultraviolet spectrum. Sunlamps are purposely designed to emit no appreciable energy shorter than λ2800. Therefore, their antirachitic effectiveness may be high, but their germicidal effectiveness is relatively low as is true for natural sunlight. The reason for the relatively high germicidal effectiveness of the low-pressure mercury arc (germicidal lamp) is the relatively

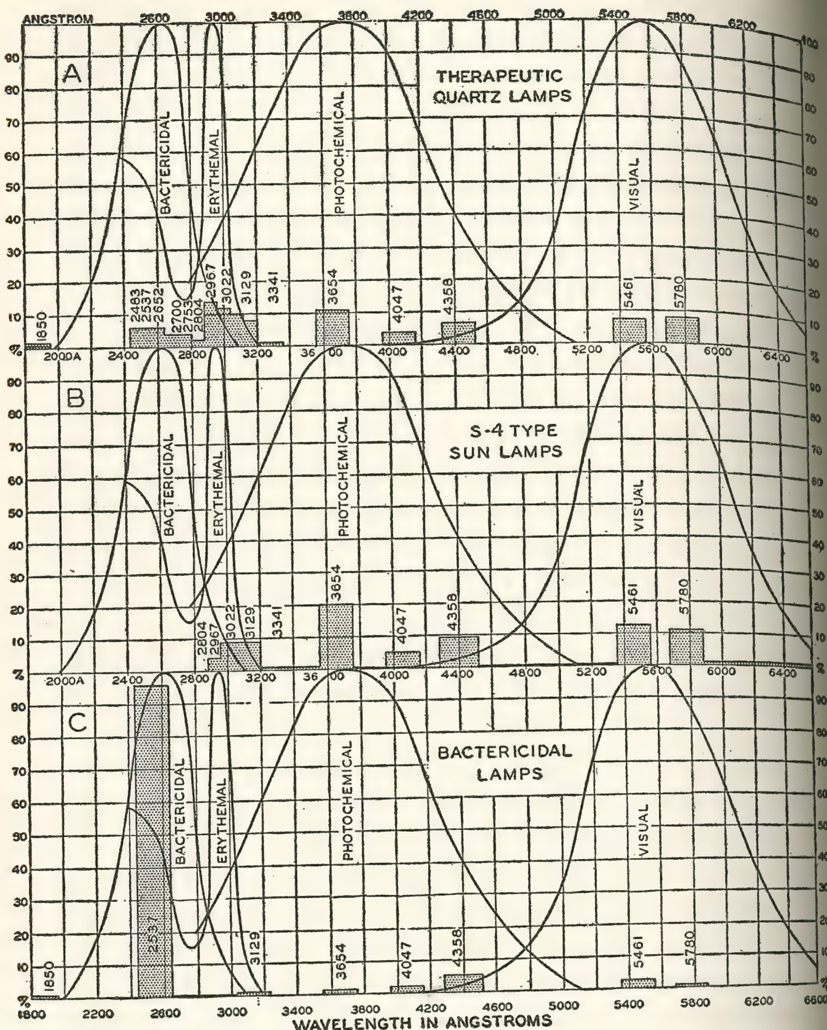


FIG. 38. Illustrating the energy of various wavelengths emitted by quartz mercury-arcs, a sunlamp, and the socalled germicidal lamp, in relation to germicidal, erythemal and visual effectiveness of radiant energy.

large amount of ultraviolet energy emitted in the region of λ2537.

GERMICIDAL LAMPS

Probably it is confusing to refer to a specific source of germicidal energy as a *germicidal lamp*. However, in the absence of a specific name for the low-pressure mercury arc, with special ultraviolet-transmitting glass, it is known by this non-distinctive and misleading term. It is not a lamp in any practical sense. It is a source of germicidal energy of relatively high germicidal efficiency. The light which it emits is incidental and generally insignificant. Throughout these discussions the term, germicidal lamp or source, is applied to this specific type of mercury arc of very low vapor pressure.

Germicidal lamps are fundamentally of the same design as corresponding fluorescent lamps. They are physically the same with the exception of the composition of the glass and the use of phosphors. The strictly germicidal lamp contains no phosphor coating on the glass tube or "bulb." However, a combination germicidal lamp and "sunlamp" can be made with a thin coating of a phosphor emitting energy in the region of λ2900 to λ3100 on the special glass which is highly transparent to the energy in the region of λ2537. Both the composition and thickness of the ultraviolet-transmitting glass of the germicidal lamp affect its transmission-factors for energy of various wavelengths. If the specific glass is thin, it may transmit enough energy in the region of λ1800 to λ2000 to produce considerable ozone. If it is too thick, it will reduce the output of the energy at λ2537. For these reasons, germicidal lamps vary somewhat in their output, but in Table XIX are presented some average results for germicidal lamps which do not produce objectionable amounts of ozone. It is seen that

practically all the ultraviolet energy is emitted in the region of λ2537 which, as seen in Fig. 34, is approximately the most effective in killing germs.

With the data in Table XIX in mind, it is well to examine the ultraviolet spectrum of the energy emitted by the germicidal lamp. This is illustrated in Plate I. Even a casual examination of the spectrum reveals how misleading a spectrogram can be. The spectral lines at λ2967, λ3024, λ3132 and λ3663 are quite conspicuous on the spectrogram in Plate I, but the combined energy of these wavelengths as seen in Table XIX is less than 5 percent of the energy in the region of λ2537. Spectrograms can be useful if properly made and interpreted, but they are no substitute for actual measurements of energy of various wavelengths.

TABLE XIX

Relative Amounts of Energy of Various Wavelengths Emitted by Typical Germicidal Lamps

Wavelength	*Relative Energy*
2537	100
2652	0.16
2804	0.04
2894	0.10
2967	0.43
3022	0.22
3130	1.9
3650	2.0

At the present time germicidal lamps are made in straight tubes of special glass and, exclusive of the ballast, are of three wattages. The 30-watt lamp is 36 inches long and has a glass tube one inch in diameter. The 15-watt lamp is 18 inches long and has a tube one inch in diameter. The 8-watt lamp is slightly more than 12 inches long with a glass tube ⅝ inch in diameter. A 4-watt lamp has a tube bent back on itself which makes it a lamp with only one base.

The average outputs of germicidal energy in the region of λ2537 of the 8-watt, 15-watt and 30-watt germicidal lamps are approximately 1.5, 3.0 and 7.2 watts, respectively. These values were obtained after the lamps had been operated 100 hours. Initially their outputs of germicidal energy were about 22 percent greater. After 2500 hours their outputs were about 24 percent less than at 100 hours of operation. The 30-watt lamp is about 50 percent more efficient in the production of germicidal energy than the 15-watt lamp. Obviously, these values are subject to change with improvements in these socalled germicidal lamps. They are not invariable among a group of lamps owing to the inevitable variation in the thickness of a given ultraviolet-transmitting glass.

It is a well-known fact that the inverse-square law should not be generally applied for distances from a source of radiant energy which are less than about five times the maximum projected dimension of the source in a given direction. However, the inverse-square law can be applied to a bare germicidal lamp, in a direction perpendicular to the lamp, at distances greater than 6 feet for the 30-watt lamp, 3 feet for the 15-watt lamp and 2 feet for the 8-watt lamp.

From spatial measurements of germicidal energy emitted by these sources, factors have been derived by means of which the total output of germicidal energy in watts may be computed from measurements of microwatts per sq. cm. at any given distance from the lamp in the range for which the inverse-square law is valid. If W represents the output of energy in the region of λ2537, M the intensity of germicidal energy at a distance d in centimeters and K is a constant, then

$$W = \frac{KMd^2}{1{,}000{,}000}.$$

Distribution measurements made at appropriate distances for the 8-, 15- and 30-watt lamps yielded values of K equal to 9.27, 9.32 and 9.76, respectively.

The foregoing discussions apply to bare germicidal lamps. If used in a reflector, the value of W will be reduced by a percentage equal to 100 minus the overall efficiency of the reflector.

In Chapter IV, units and terminology are discussed. The term *viton* was coined for use for various effects of ultraviolet energy. Obviously in the case of germicidal effectiveness of sources of ultraviolet energy, the energy of various wavelengths must be weighted according to the germicidal effectiveness of energy of each wavelength as shown in Fig. 34. However, such weighting is scarcely necessary in the case of the socalled germicidal lamps for the reason that practically all the ultraviolet energy is emitted in the region of maximal germicidal effectiveness. In other words, the watts of energy emitted in the region of $\lambda 2537$ are a direct measure of the germicidal flux.

If it is desired to continue the system in which the viton is used, a G-viton could be defined as being equivalent to one milliwatt or microwatt of radiant power of maximal germicidal effectiveness. The magnitude of the unit depends upon the effective intensities of germicidal flux determined in practice. If these socalled germicidal lamps were the only sources of germicidal flux in extensive use, such a term as G-viton would not be needed. Watts, milliwatts and microwatts of radiant power in the region of $\lambda 2537$ serve very well. Besides, the germicidal effectiveness of this energy varies with different organisms. Therefore, a G-viton would have different lethal values depending upon the organism to be killed.

GERMICIDAL UNITS AND TERMS

In Chapter IV the need for units and terms for any given biological effect of radiant energy is discussed and a complete system was developed using erythemal effect as an example. A similar system could be developed for germicidal effectiveness. However, some of the need for it and for certain terms disappears owing to the fortuitous accident that practically all the germicidal energy emitted by the new low-pressure mercury vapor lamp—socalled germicidal lamp—is concentrated in the spectral region of $\lambda 2537$ which is also the spectral region of maximum germicidal effectiveness of radiant energy. Therefore, for all practical purposes when dealing with this socalled germicidal lamp, *germicidal energy* is numerically equivalent to germicidal flux. To be strictly correct its output in germicidal microwatts should be termed *germicidal radiant power* instead of *germicidal radiant energy*. The microwatt, milliwatt, and watt are units of power. The microwatt-minute as well as the watt-hour are units of energy. Therefore, a microwatt actually represents radiant power and microwatt-minutes represent energy.

Microwatts per sq. cm. represent intensity of radiant power. Microwatt-minutes per sq. cm. represent the total energy incident upon a sq. cm. of surface. However, the word *power* is used in so many senses that it is often less misleading to use the term *germicidal radiant energy* when we actually mean *germicidal radiant power*. The unit of measurement used in any case identifies the meaning.

In these discussions of radiant energy and its different biological effects it is desirable to use the metric system of units wherever possible. We may adhere to this in basic considerations, even though we use feet, cubic feet, gallons, etc., when dealing with the strictly engineering aspects of practical applications.

For those who wish to convert microwatts per sq. cm. into milliwatts per sq. ft. or vice versa,

one milliwatt per sq. ft. equals 1.076 microwatts per sq. cm.
one microwatt per sq. cm. equals 0.929 milliwatt per sq. ft.

For many practical purposes the two units may be considered to be equal.

SURVIVAL-RATIO OF BACTERIA

In the application of germicidal energy, *exposure* is a matter of total incident energy per unit of area. Therefore, exposure is a product of the intensity E and the time t. From much experience with various exposures and their bactericidal effectiveness we find that intensity is conveniently measured in microwatts per sq. cm. (or milliwatts per sq. ft.). For a powerful source such as the germicidal lamp, time is conveniently measured in minutes. In some applications in which killing of bacteria takes place quickly, time may be measured in seconds. (See Plate XIV.)

The survival-ratio is the fraction of the original concentration P_0 of bacteria surviving after a given exposure. The concentration of bacteria is the average number per unit area in the case of surfaces. When dealing with volumes such as air or water, the concentration of bacteria is the number per unit volume.

From the results of thousands of cultures of exposed air and water containing B. coli, it appears that the exponential relationship between survival-ratio and exposure holds approximately for an extensive range sufficient for practical purposes. This relationship may be represented for the exposure of bacteria in air as follows:

$$\frac{P}{P_0} = e^{-KEt} \tag{1}$$

where e is the base of the natural system of logarithms

E is the intensity of germicidal flux
t is the time
Et is the exposure
K is a constant depending upon the humidity, etc.

When the exponent of e (about 2.718) is minus unity the survival-ratio equals 0.368. The exposure Et, corresponding to a survival of 36.8 percent, has been termed a *lethe* by Wells.[35] We have also termed it a *unit lethal exposure*. Obviously, if the exposure for one given survival-ratio has been accurately determined, this exponential law can be drawn as a straight line as in Figs. 36 and 37 when the ordinate scale is logarithmic. By extending this straight line through this one well-established point to a survival-ratio of unity for zero exposure, and also in the other direction, the survival-ratios for other exposures are readily obtained. Of course, it is far better to establish several points by means of actual experimental data.

Obviously the survival-ratio of bacteria is one minus the fraction killed. For example, if 0.368 of the original number of bacteria survived, 0.632 were killed. If one wishes to express the survival in percent, the term *survival-ratio* should be replaced by percent surviving. Survival-ratios vary from 1 to 0. Percent surviving varies from 100 to 0. The *percent killed* is 100 minus the percent surviving and varies from 0 to 100.

For the exposure of B. coli in water we have found it convenient to express the exponential relationship between exposure Et and survival-ratio as follows:

$$\frac{P}{P_0} = e^{-\frac{Et}{Q}} \tag{2}$$

where Et is the exposure (intensity $\times$ time), Q is the unit lethal exposure or the exposure which results in a survival-ratio of 0.368 or 63.2 percent killed.

As seen later, the resistivity of bacteria to germicidal energy varies considerably. Therefore, it is questionable whether such terms as *lethe* and *unit lethal exposure* are of much practical value. Their numerical values must be expressed in microwatt-minutes per sq. cm. or milliwatt-minutes per sq. ft. Inasmuch as these numerical values vary with the resistivity of the bacteria, exposure for a given percent survival or kill also varies with different kinds of bacteria.

A GERMICIDAL UNIT OF EXPOSURE

It appears that a term of more practical value would be one which substitutes a word or two, or a letter or two, for the exposure *Et*. This would be a term for a given number of microwatt-minutes per sq. cm. An exposure unit *EU* might be used but this could be confused with an erythemal unit of exposure. Therefore, the letters *GU* might be used to indicate one germicidal unit of exposure. For the new germicidal lamp, germicidal energy and germicidal flux are numerically nearly equal. For any other source of germicidal energy, the energy of various wavelengths would have to be weighted in accordance with their germicidal effectiveness. This converts germicidal energy into germicidal flux which, fortunately in the case of the new germicidal lamp, is practically the same. (See Plate I.)

Owing to the high germicidal efficiencies of the new germicidal lamps, applications of germicidal energy will almost entirely involve their use. Taking this into consideration, along with the fact that the resistivity of various types of bacteria differs, it appears more practical to measure exposure *Et* in such units as microwatt-minutes per sq. cm. For brevity and convenience, one germicidal unit of exposure *GU* would be equivalent in germicidal effectiveness to one microwatt of λ2537 incident upon a projected area of one square centimeter for a period of one minute. Therefore, one germicidal unit of exposure would be expressed as follows:

one *GU* equals one microwatt-minute per sq. cm.

The size of this unit is such that fractions of it would not occur very often in practice.

It is emphasized again that the resistivity of various micro-organisms varies over wide limits. Even B. coli are more resistant in moist air than in dry air. They are at least several times more difficult to kill in water than in average air. Therefore, any unit of exposure based upon even a given type of bacteria would not have a fixed germicidal value. However, a unit of exposure based upon germicidal effectiveness as illustrated in Fig. 34 and Table XVII, is of more direct, practical and universal value. This should become even more evident in later chapters.

Those who insist upon continuing the mixture of two systems of units could define the germicidal unit of exposure as follows:

one *GU* equals 0.929 milliwatt per sq. ft.

KILLING VARIOUS ORGANISMS

Although a great deal of work has been done toward ascertaining the lethal exposure necessary to kill various organisms,[36] it is impossible to coordinate the results owing to a lack of data pertaining to the intensity and spectral character of the radiant energy employed. With the advent of the socalled germicidal lamp with its high germicidal efficiency, and its concentration of ultraviolet energy at λ2537, it is inevitable that much experimental work will be done with various organisms. It will be possible to coordinate the results if simple measurements of energy and

exposure are also made. Although the output of germicidal flux varies among different germicidal lamps, owing to variations in the thickness of the glass, a simple specification of distance of the lamp from the exposed material will indicate the approximate intensity of germicidal flux. (See Plates VI, VIII, IX and XI.)

It is convenient to use the relatively harmless B. coli for fundamental investigations, as discussed in these chapters, but it should be emphasized that the exposure necessary for a given survival-ratio or percent kill varies not only with the organism but even with the same organism in different environments. The resistivity of most disease-producing bacteria and viruses appears to vary from about one to ten times that of B. coli. In practice this results in different survival-ratios for a given exposure. Obviously the same survival-ratio may be obtained for different pathogenic bacteria and viruses with suitably different exposures. Factors of safety in the design of an installation of germicidal lamps can readily be provided to take into account the higher resistivities of some of these organisms.

When spore-forming bacteria, fungi and yeast are to be killed, much greater exposures are necessary than in the case of pathogenic organisms. When time is limited, the intensity of germicidal flux must be greatly increased. Such organisms appear to be from 2 to 50 times more resistant than B. coli. We have found the resistivity of plants to damage by energy of $\lambda 2537$ to vary greatly. In the case of bacteria which do not possess an impenetrable covering, adequate germicidal exposures are bound to be destructive. However, there may be some whose outer layers or coatings are not sufficiently transparent to energy of $\lambda 2537$ to permit the energy to reach vital regions.

Experiments with paramecia, insects and worms indicate that germicidal energy will kill them if it penetrates them with sufficient intensity for a sufficient period of time.

Small earthworms, irradiated in a few drops of water to keep them moist, were killed by exposures to erythemal energy equivalent to ten times that which produces a minimum perceptible erythema on average untanned human skin. They were killed in 7 minutes at a distance of 15 cm. from an S-4 sunlamp and in one minute at the same distance from a 360-watt quartz mercury arc. Paramecia in water succumbed to exposures about twice that necessary to produce an MPE on untanned skin. A 30-watt germicidal lamp killed small earthworms in 20 to 80 minutes at distances of 10 to 50 cm., respectively.

Sufficient exposure to visible energy from a tungsten-filament lamp, projected through thick lenses to absorb the ultraviolet energy and through a water-cell to absorb most of the infrared energy, will kill paramecia. An exposure which killed paramecia in water in 75 minutes killed them in 1 to 2 minutes when a slight amount of eosine or fluorescein was added to the water. These socalled photosensitizers had no apparent effect on the paramecia in subdued light. In these cases they increased the lethal effect of intense visible energy so that the latter was as effective as a considerable exposure to ultraviolet energy.

Fig. 39 is made from a print through an actual plate of glass whose surface was infected with B. coli. The plate was placed in a quartz spectrograph and exposed 45 and 30 minutes, respectively, to the spectrum of a mercury arc. It was then incubated for 24 hours and a contact print was made through it on photographic paper. Each tiny circle is a print of a colony of B. coli. The illustration is of interest only in showing the spectral range of germicidal effectiveness of ultraviolet energy. Owing to the fact that the radiant energy strikes the seeded plate quite obliquely, the gaps in the mercury spectrum are not clearly defined

although there are evidences of some of them. Quantitative results of the germicidal effectiveness of ultraviolet energy of various wavelengths can be obtained by this means if proper care is taken.

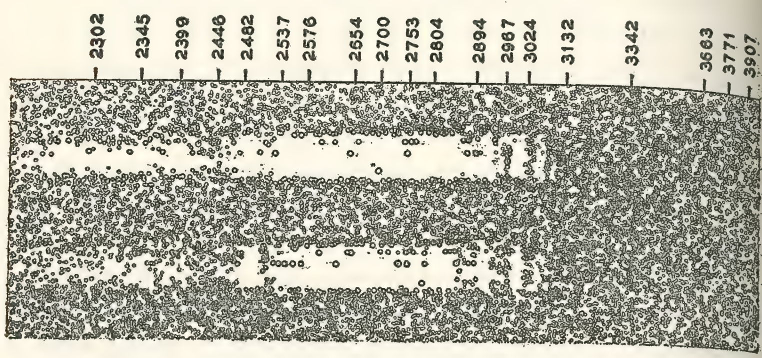


FIG. 39. Showing the germicidal effect of the spectrum of a mercury-arc focused upon an agar plate seeded with B. coli. A contact photographic print was made after the plate was incubated 24 hours.

THERAPEUTIC EFFECTIVENESS

Quartz mercury arcs have been used quite extensively for therapeutic purposes for many years. These emit ultraviolet energy of various wavelengths including those in the spectral region of maximal germicidal effectiveness. With the advent of the germicidal lamp emitting considerable energy in the region of λ2537, the question arises as to the possible therapeutic value of this germicidal energy. Obviously some answers to this question could have been obtained long ago by ascertaining the results obtained with a quartz mercury arc with and without a filter which would absorb the ultraviolet energy shorter than λ2800.

Although erythemal effectiveness of ultraviolet energy is in no direct sense a measure of the antirachitic or other therapeutic effectiveness, it provides a starting point for discussion. The erythemal effectiveness of ultraviolet en-

ergy of various wavelengths is illustrated in Fig. 30. According to the work of the author and his colleagues, the erythemal effectiveness of λ2537 is about 80 percent of the maximal erythemal effectiveness which is at λ2967. The curve that was standardized about a decade ago shows a lower value for this secondary maximum. However, continued work along this line leads the author to the conclusion that this standardized value is too small. However, it is well known that the erythemal effect due to λ2537 is relatively superficial and evanescent and, therefore, the erythemal effectiveness depends considerably upon the time elapsed after exposure before the appraisal is made.

The transmission-factor of the skin is very low for ultraviolet energy in the region of λ2537. This is illustrated in Table IX. If, for example, the antirachitic effect of ultraviolet energy is due to the irradiation of ergosterol in the fatty substance underlying the outer coating of the skin, appreciable energy must reach its goal in order for it to be effective. The skin over various parts of the human body varies widely in its physical characteristics. This is also true of animals. Furthermore, it is known that only relatively restricted areas of a living body need to be irradiated in order to prevent and to cure rickets. In addition to this Gerstenberger [22] found that very low intensities of energy between λ2800 and λ3200 cured rickets in partially clothed babies. Therefore, there is encouragement in the hope, and even belief, that germicidal lamps which emit ultraviolet energy largely in the region of λ2537 may have sufficient antirachitic effectiveness to be useful.

Actual clinical evidence is becoming available which appears to indicate that germicidal lamps have possibilities in preventing and curing rickets and, by extension, in other branches of therapeutics. Bunker [42] determined the effectiveness of ultraviolet energy of various wavelengths in

producing equal healing of rachitic rats. He found that energy of λ2537 was 54 percent as effective as energy of λ2967. Considering the high efficiency of germicidal lamps in producing energy in the region of λ2537, one may be led to expect that these lamps could be as effective as socalled sunlamps of much higher wattage which purposely are restricted to energy longer than λ2800.

In addition to the foregoing there is some evidence that, in the use of germicidal lamps for killing bacteria in poultry houses, chicks have more vitality and their bone-ash and comb development are normal compared with chicks which are not exposed to the energy from germicidal lamps.

With these qualifications it is interesting to note that a 30-watt General Electric germicidal lamp emits 400,000 E-vitons compared with 68,000 E-vitons emitted by the S-1 sunlamp, 50,000 by the S-4 sunlamp, and 25,000 by the RS sunlamp. The erythemal efficiency, as measured by the E-vitons produced per watt, is many times greater for germicidal lamps than for the foregoing sunlamps.

In addition to the foregoing there are other possible therapeutic uses for germicidal lamps. Those interested in superficial skin affections will do well to investigate these new highly efficient sources of energy in the middle ultra-violet region. Of course, if they are used to irradiate the body directly, goggles should be worn to protect the eyes. Ordinary clear glass should provide adequate protection. In using them one should not overlook other destructive effects such as fading and the killing of plants.

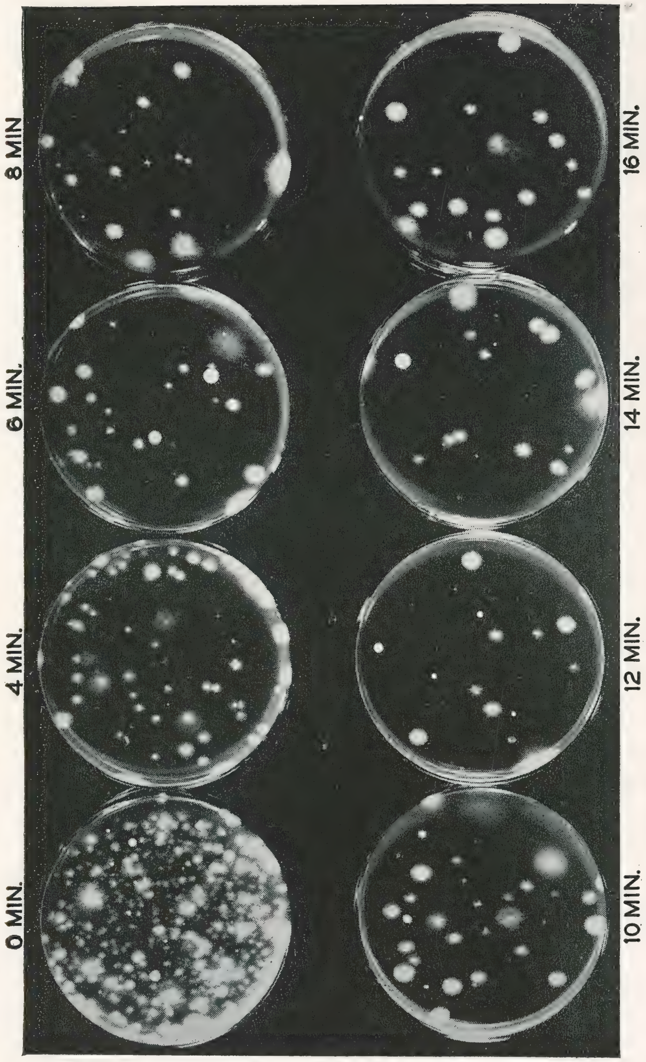


PLATE VI. Fungi and fungi spores sprayed on nutrient in petri dishes, subjected to intensity of germicidal flux of 150 microwatts per sq. cm., for the number of minutes indicated, and then incubated. Most organisms were killed in 4 minutes but some survived after 4 times this exposure. Without irradiation all dishes would have appeared similar to the upper left-hand one.

Disinfecting Controlled Air

FOR A half century it has been known with certainty that ultraviolet energy kills bacteria, or at least renders them incapable of reproduction. For eons before this became known, sunlight has kept the population of micro-organisms outdoors within reasonable bounds. This is accomplished by sunlight and skylight which are relatively weak in germicidal flux compared with that provided by certain artificial sources. Indoors the germicidal effectiveness of daylight and of artificial light is so relatively insignificant as to be generally negligible. The indoor air is relatively confined, especially during the cold months, and it is contaminated with germs from human beings. One person breathes air which has been breathed by another person or by many persons. This communal air is further contaminated by talking, coughing and sneezing. Thus we breathe air containing germs and viruses.

It is known that infectious agents enter the body by way of the respiratory tract. We are more or less educated to avoid infection by being careful about eating contaminated food and drinking infected water. We may be careful of our actual contact with other human beings. We may wash our hands for the same reason. However, human beings breathe the communal air exhaled by others and they catch colds, get the measles, acquire tuberculosis, and suffer other infections through the process of breathing infected air. Sanitary engineering, bacteriology and hygiene have made great contributions to health and human welfare. They have pursued a variety of avenues and have developed into many special fields of application. But indoor air has

been generally neglected as a source of infection excepting by diluting it with fresh air, generally to a limited extent, in our interiors. The air [37] is a vehicle by which infectious organisms gain entrance to the human body just as milk and water have been widely recognized to be.

With the advent of efficient and effective sources of germicidal energy, a great impetus has been given to the disinfection of air not only for the prevention of illness but for many other purposes. However, it is necessary to ascertain the laws and methods pertaining to their use. Controlled laboratory investigations provide the basis for the technology of use. Investigations in the field must have a sound basis for planning them. They contribute to the total knowledge largely by confirming in practice the findings of the laboratory. This is generally true of nearly all practices that involve the efficiency, health and welfare of human beings as well as many other practices. Eventually the foundation of knowledge is available for practical installations.

Air in interiors is controlled in complete air-conditioning installations. In other interiors it is partially controlled. In many cases it circulates in a given interior more or less accidentally. If adequate window areas were open to the outside air at all times, the need for disinfecting the indoor air would be greatly reduced. If interiors had adequate controlled ventilation and provided adequate make-up air from outdoors, the opportunities for the use of germicidal lamps would be greatly reduced. However, such conditions are relatively rare excepting during the summer months.

There are many special cases where it is desirable to kill all micro-organisms in the air, or at least to reduce their number to a desirable minimum. In these cases there may

be yeast cells and resistant fungi. Apparently some of these are many times more difficult to kill than pathogenic organisms. Almost universally in occupied interiors it is desirable to kill pathogenic germs and viruses. These vary somewhat in their resistivity to germicidal radiant energy but are generally much more readily killed than yeast cells. B. coli are fairly representative of these pathogenic organisms and, therefore, are commonly used in basic investigations. It is only necessary to determine the relative resistivity of any other organism in order to apply the data obtained with B. coli to the other organism. Unless otherwise stated, the present discussions apply to B. coli.

DISINFECTING CONTROLLED AIR

The first of a series of laboratory investigations of the effectiveness of germicidal lamps in disinfecting controlled air was prosecuted by Luckiesh and Holladay [38] with the apparatus illustrated in Fig. 40. This apparatus was about 15 feet long and was made with steel framework and covered with sheet steel. It was carefully designed to provide, by means of the blower, a wide range of air velocities through the cylindrical duct. A variety of screens at the inlet to the duct and a set of baffles near its outlet were perfected to insure uniform horizontal flow of air through the duct. A 30-watt, 115-volt, 36-inch General Electric germicidal lamp was installed in the axis of the cylindrical duct whose diameter was two feet. The inner surface of the duct could be lined or painted with material having various reflection-factors for the germicidal energy of λ2537. The air could be humidified by a fine mist of water-vapor produced by an atomizer. The humidity and temperature could be determined at all times by appropriate devices. B. coli could be injected into the air by the vaporizer.

Samples of air were taken before and after passing through the irradiated duct by the two aeroscopes located as shown. Each aeroscope consisted of a standard petri dish, a 60-degree glass funnel inverted over the dish and a suitable cylindrical container containing an inlet and outlet for the air to be sampled. When air is drawn through the

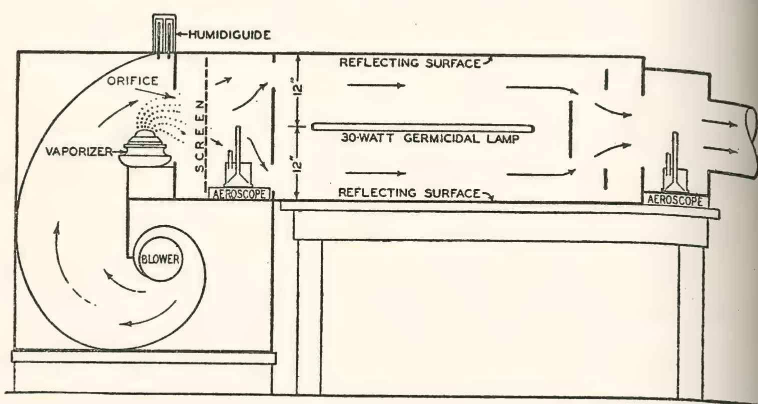


FIG. 40. Illustrating major details of apparatus for fundamental researches of the lethal effect of germicidal energy on air-borne B. coli under controlled conditions of air-flow, humidity, temperature and exposure.

aeroscope at about one cubic foot per minute, its momentum causes the bacteria in the air to be fairly uniformly deposited over the surface of the culture medium in the petri dish. (See Fig. 49.)

The Walton atomizer under working conditions atomizes from 1.5 to 2 cc. of water per minute, depending upon the elevation of the liquid in its receptacle. This atomizer was found more constant than others used in preliminary investigations. This water was infected with B. coli cultivated from some obtained from W. F. Wells. The bacteria for infecting the air in the duct were grown in Bacto Nutrient Broth for about 24 hours at a temperature of

37.5° C. A number of culture plates were prepared in advance of each run by coating the flat bottoms of petri dishes with standard preparations of Levine's Eosin Methylene Blue Agar. After these plates were seeded with bacteria from the samples of air drawn from the duct, the plates were incubated for periods of about 24 hours at 37.5° C.

The criterion for determining whether an irradiated bacterium survived the irradiation was its ability to develop a colony when seeded on a suitable medium and incubated at an optimum temperature. As the air left the blower and before it reached the portion of the duct containing the germicidal lamp, it was infected with B. coli by means of the atomizer. After being uniformly mixed, a sample totaling five cubic feet was withdrawn at the rate of approximately one cubic foot per minute through one aeroscope where an adequate proportion of the bacteria was precipitated on the culture medium in the petri dish. After the air had been irradiated during its passage through the duct, a similar sample was withdrawn from the other end of the duct. These two samples were taken simultaneously. The cultures were then incubated for 24 hours and the numbers of colonies in the dishes were counted and compared. At first much difficulty was experienced in obtaining representative samples. Much of this difficulty was eventually overcome by the use of the Walton atomizer, cheesecloth filters, screens, and attention to other details. Although this method of air-sampling was satisfactory for obtaining relative survival-ratios, before and after irradiation of the air, since that time the author and his colleagues, L. L. Holladay and A. H. Taylor, have developed more precise methods.[39] These are discussed in Chapter VII.

Inasmuch as the total germicidal flux emitted by these germicidal lamps varies somewhat initially, decreases dur-

ing their life, and also is affected by accumulated dust, the results discussed herewith apply to a 30-watt General Electric germicidal lamp emitting a total of 11 watts in the region of λ2537. After a long series of tests was made with the apparatus illustrated in Fig. 40, involving thousands of cultures made from as many air samples, it became possible to compute the results which would be obtained in ducts of various sizes and with various velocities of air. In all cases the results apply to 30-watt germicidal lamps, each emitting 11 watts of germicidal flux. As in all designing, an adequate factor of safety should be provided for depreciation. Its magnitude depends upon various conditions as well as upon the kind of organisms involved and the degree of disinfection desired.

REFLECTION-FACTOR OF DUCT LINING

Inasmuch as considerable depths of air do not appreciably absorb radiant energy of λ2537, it is advantageous to use ducts as large in cross-section as is practicable. In the initial investigation, a cylindrical duct two feet in diameter was used. The inner lining of this duct was painted with an aluminum paint having a reflection-factor for energy at λ2537 of about 70 percent. This lining could be covered when desired with a removable one of dull black paper which reflected practically none of the germicidal energy. Many measurements indicated that the aluminum paint increased the intensity of germicidal energy, as measured at the inner surface of the duct, by an average of 70 percent.

The results obtained with the black and aluminum linings are presented in Fig. 41 where the intensities of germicidal energy are plotted as measured at various places along the inner lining of the duct parallel to the 36-inch germicidal lamp located in the axis of the duct. The intensities of germicidal energy are measured in microwatts per sq. cm. They can be transformed into milliwatts per sq. ft. by multiplying them by 0.929. There is some advantage in expressing fundamental data in the metric system of units.

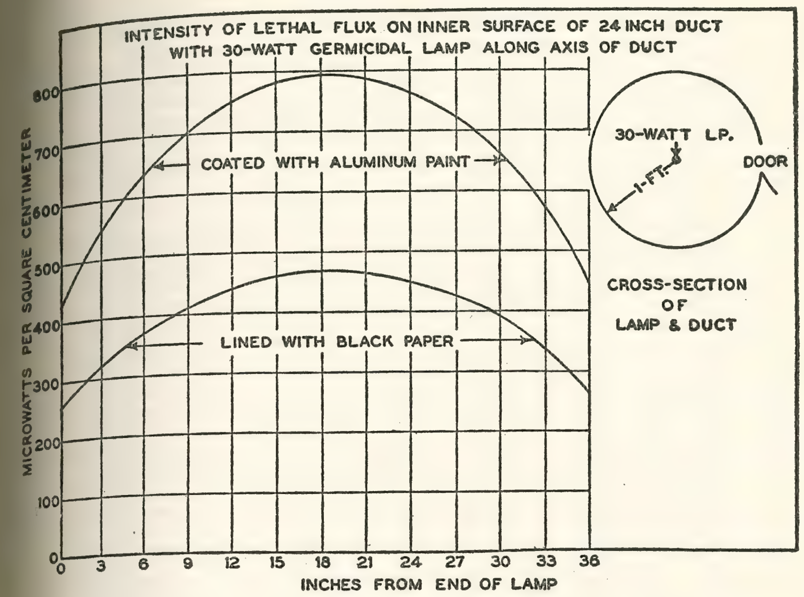


Fig. 41. Showing the intensities of germicidal energy along the inner lining of the experimental duct 2 feet in diameter measured along a 36-inch strip, equivalent to the length of the germicidal source. The effect of a high reflection-factor of the lining is obvious.

This need not be confusing inasmuch as the two units are practically equal numerically. When intensities of germicidal energy are presented in milliwatts per sq. ft., they can be transformed into microwatts per sq. cm. by multiplying them by 1.076. The average intensity of germicidal flux one foot from the germicidal lamp along the length of 36 inches was 389 microwatts per sq. cm. when the duct was lined with dull black paper. When painted with the alumi-

num paint the average intensity was 660 microwatts per sq. cm.

In Fig. 42 are presented some of the data obtained in killing B. coli in air as it passed through the 24-inch cylin-

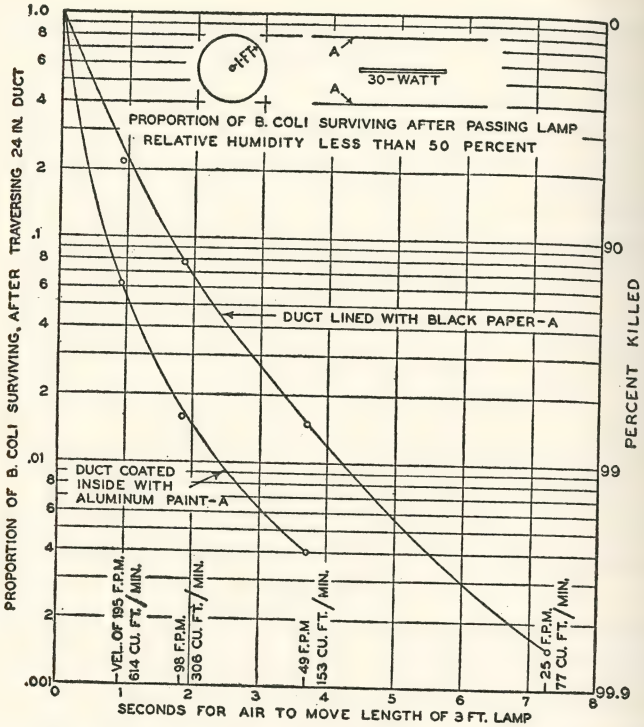


Fig. 42. The survival-ratio of air-borne B. coli decreases as the velocity of air through a 2-foot duct decreases. The influence of the reflection-factor of the inner walls of the duct is also shown.

drical duct at different velocities. By multiplying the volume of a 3-foot length of duct by the rate at which the air moved, the rate of disinfection of air in cubic feet per minute was determined for one 30-watt, 36-inch germicidal lamp located axially. By sampling the air simultaneously at

the intake and the outlet of the 24-inch duct, the survival-ratios of B. coli for the various conditions were determined. For example, when the air passed through the duct at the rate of 614 cu. ft. per minute, the survival-ratio was about 0.05 when the lining was painted with aluminum paint and about 0.22 when this lining was covered with the dull black paper. The percent killed in these two cases was 95 and 78, respectively. For convenience the percentages killed, corresponding to various survival-ratios, are indicated at the right-hand side of Fig. 42.

The advantage of an aluminum lining for air-ducts in which germicidal lamps are installed is considerable, but these linings would have to be cleaned periodically. Obviously the lamps should also be kept clean.

EFFECT OF SIZE OF DUCT

From the basic data it was possible to compute [38] the results for ducts of various shapes and sizes for certain survival-ratios of B. coli. For more resistant organisms the survival-ratios would be greater in any given case unless more germicidal energy were provided. As already emphasized, no factor of safety is included in these designs and computed results.

Inasmuch as germicidal energy of λ2537 is not appreciably absorbed by depths of air encountered in interiors, the efficacy of each germicidal lamp in disinfecting air increases with the size of the duct. This is substantiated by Fig. 43 for four square ducts varying in cross-section and length. For example, the duct 4 feet square was assumed to be 10 feet long and to contain two germicidal lamps, end to end, along about 6 feet of the central portion of the axis. The duct 16 feet square was assumed to be 40 feet long and to contain 8 germicidal lamps, end to end, along about 24 feet of the central portion of the axis. The data

strikingly illustrate the effect of the size of the duct upon the volume of air *disinfected per germicidal lamp.* A survival-ratio of 0.01, which means 99 percent killed or rendered incapable of reproduction, is used as a basis for computations. As the cross-section increases from 2 feet square to 16 feet square, the volume of air disinfected to

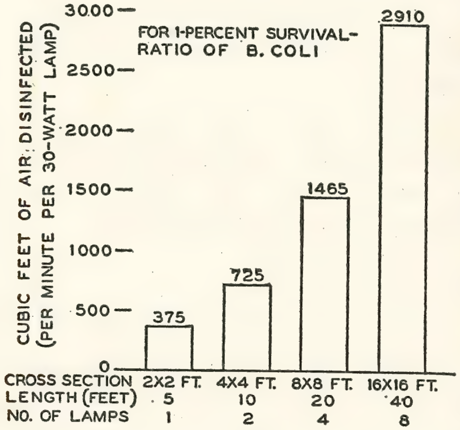


FIG. 43. The volume of air disinfected per minute per 30-watt germicidal source rapidly increases as the size of the duct increases.

this degree, per minute per germicidal lamp, increases from 375 cu. ft. per minute to 2910 cu. ft. per minute. In these cases the inner linings of the duct were assumed to reflect none of the incident germicidal energy.

The contribution to the efficiency of disinfecting air by reflection of germicidal energy by the inner surfaces of the air-duct increases rapidly for the higher reflection-factors. This is illustrated in Fig. 44 for a survival-ratio of 0.01 or 99 percent killed. It also illustrates that the increase is not appreciable if the reflection-factor of the inner surfaces is allowed to depreciate to values less than 30 percent. Inasmuch as aluminum surfaces have a high reflection-

factor for germicidal energy, it is desirable to use aluminum and to keep it reasonably clean. However, if maintenance is too difficult or impracticable, the inner surfaces of the duct need not be considered in designing such installations. In any case the germicidal lamps should be given attention.

The data presented in Fig. 45 show the greater

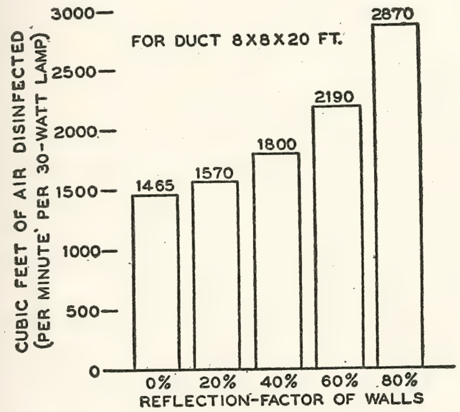


FIG. 44. Showing the effect of the reflection-factor of the inner walls of an air-duct on the volume of air per minute per 30-watt source in which 99 percent of the air-borne B. coli are killed.

efficiency of the larger duct for a considerable range of survival-ratios of B. coli and percentages killed. They also show the great increase in volume of air disinfected per lamp if one is satisfied with lower percentages of organisms killed or rendered impotent. For example, for a survival-ratio of 0.1 or 90 percent killed, the volumes of air disinfected per germicidal lamp are 1600 and 6400 cu. ft. per minute for the smaller and larger ducts, respectively. In other words, at this survival-ratio the larger duct is 4 times as efficient as the smaller one. This great difference in efficiency continues to hold approximately for smaller survival-ratios or larger percentages of kill. For a survival-

ratio of 0.01, or 99 percent killed, the volumes of air disinfected per germicidal lamp are 725 and 2910 cu. ft. per minute for the smaller and larger ducts, respectively. (See Fig. 43.)

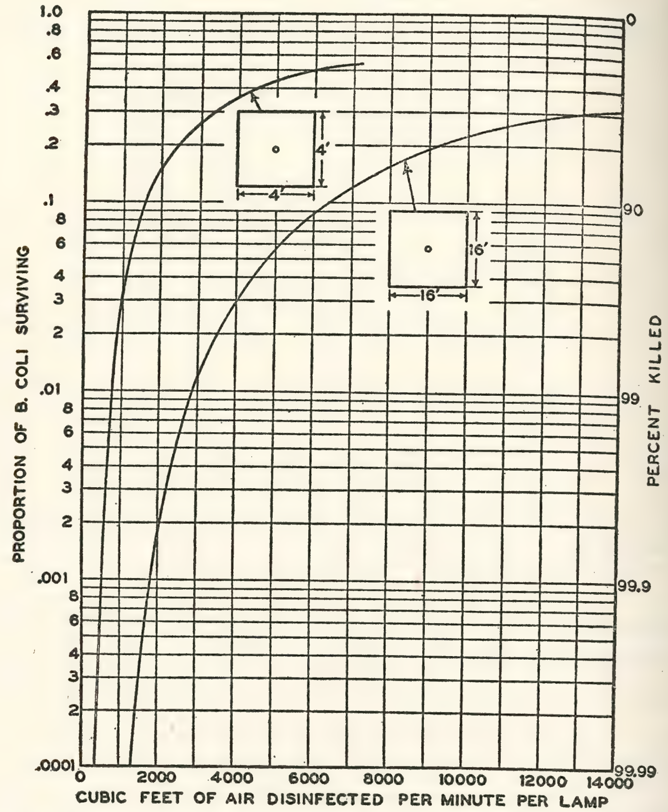


FIG. 45. Illustrating the advantage of air-ducts of large cross-section for disinfecting air with germicidal sources.

If it is necessary to disinfect larger volumes of air per minute, more germicidal lamps can be installed in a given duct. For example, instead of placing one row of 8 lamps end to end, as in the largest duct illustrated in Fig. 43, four such rows could be used parallel to the axis. This would result in installing 32 germicidal lamps instead of 8 in the duct 16 feet square. The result would be that about 8 times as much air could be disinfected in a given time in the same duct. This means that the velocity of the air could be increased to 8 times that when there were only one-eighth as many germicidal lamps in the duct. In fact, under these conditions of higher velocity of air, computations indicate that the volume of air disinfected to a given survival-ratio would be somewhat greater per germicidal lamp. As shown elsewhere,[38] with 8 instead of 2 germicidal lamps in the duct 4 feet square, and 32 instead of 8 germicidal lamps in the duct 16 feet square, the volumes of air for a 99-percent killing of B. coli would be about 6600 and 100,000 cu. ft. per minute with walls having a negligible reflection-factor.

There appears to be little difference between ducts of circular and square cross-sections of the same area. The important factor is the depth of air traversed by the germicidal energy emitted by the lamp before it suffers appreciable or total absorption at the inner walls of the duct. Placing the lamps crosswise in the duct does not appear to achieve results greatly different than when they are installed axially. In large ducts of considerable length this might be done for some practical reason. However, it is possible that the germicidal lamps might gather more dust when located transversely than when they are located along or near the axis. Furthermore, when placed axially in ducts, sufficiently large for a person to enter, they should be less obstructive of the passage and could more readily be kept clean.

In Fig. 46 a duct of rectangular cross-section is considered. The height of the duct is 2 feet and the germicidal lamps are located axially end to end. The width D of the

duct is considered in the range from 2 feet to 6 feet. Here again the effect of the greater depth of air is evident. However, the restriction of the height of the duct to 2 feet reduces the efficiency of the duct regardless of its width. Figs. 43 and 44 emphasize the desirability of increasing both

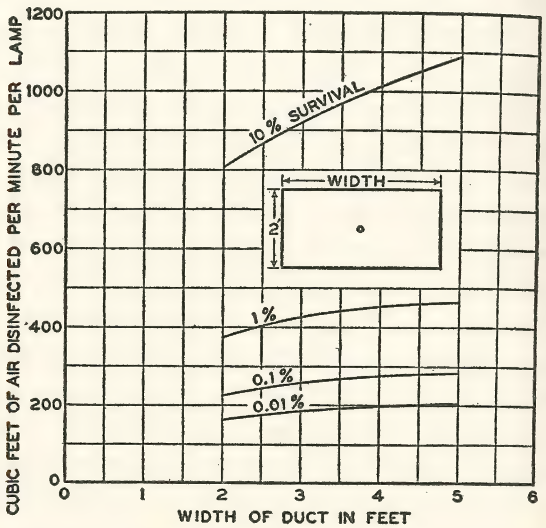


FIG. 46. Increasing one dimension of a rectangular duct increases the efficiency of disinfection but not as strikingly as increasing both dimensions of the cross-section.

dimensions of the cross-section of the duct as much as is practicable. Fig. 46 also emphasizes how much greater a volume of air can be treated if one is satisfied with higher survival-ratios or lower percentages killed. For example, for a 90-percent kill about 5 times as much air can be treated per germicidal lamp as for a 99-percent kill.

It should be obvious that baffles should not be used in air-ducts in which air is being disinfected by germicidal energy. They are bound to intercept some of this energy which thereby will suffer more or less absorption.

In Table XX is presented a summary of volumes of air disinfected per germicidal lamp for ducts of various cross-sections and lengths. It is emphasized that the total cubic feet of air disinfected per minute in each case is obtained by multiplying the volume per minute per germicidal lamp

TABLE XX

Cubic Feet of Air Disinfected per Minute per 30-Watt, 36-Inch, General Electric Germicidal Lamp for Various Percentages of Air-Borne B. Coli Killed or Rendered Incapable of Reproduction. These Values Were Computed for a Relative Humidity of 35 Percent and for Walls of the Ducts Reflecting No Germicidal Energy. If the Reflection-Factor of the Walls Were 65 Percent, the Volumes of Disinfected Air Would Be Increased 50 to 60 Percent

Duct		*Number of Germicidal Lamps*	*Cubic Feet of Air per Minute per Lamp for Percentages Killed*			
Cross-Section (feet)	*Length (feet)*		*90%*	*99%*	*99.9%*	*99.99%*
2 ft. diam.	5	1	725	340	215	156
4 ft. diam.	10	2	1430	685	420	305
8 ft. diam.	20	4	2900	1360	850	615
2 x 2	5	1	805	375	225	165
3 x 3	9	2	1220	550	345	248
4 x 4	10	2	1570	725	470	330
8 x 8	20	4	3020	1465	915	660
16 x 16	40	8	6200	2910	1835	1300
2 x 3	5	1	920	425	260	185
2 x 4	6	1	1015	455	275	200
2 x 5	6	1	1090	465	285	205
4 x 4	10	8	1750	832	535	390
16 x 16	40	32	6850	3250	2075	1525

by the total number of germicidal lamps in the duct. The volumes of disinfected air per minute per germicidal lamp are presented for four percentages killed of the total original air-borne B. coli. These percentages killed, 90, 99, 99.9 and 99.99, correspond to survival-ratios of 0.1, 0.01, 0.001 and 0.0001, respectively. The walls of the ducts were assumed to reflect none of the incident germicidal energy. Elsewhere [38] the volumes of disinfected air are also computed for the same ducts assuming that the walls reflect 65

percent of the germicidal energy. This results in volumes of disinfected air from 50 to 60 percent greater than those presented in Table XX.

The temperature of the air does not appear to affect the resistivity of micro-organisms for the range of temperatures commonly encountered in interiors and in ventilating systems.

EFFECT OF HUMIDITY

All the data presented in the foregoing discussions in this chapter were experimentally determined, or computed from basic data, for an average relative humidity of 35 percent. However, higher relative humidities increase the resistivity of the B. coli as indicated by the higher survival-ratios, and correspondingly the lower percentages killed, for a given exposure of the air-borne bacteria. At least the survival-ratio for a given exposure to germicidal energy is definitely higher when the humidity is high than when it is low. As seen in a later chapter, the resistivity of B. coli in water is 5 to 10 times that in air.

With the apparatus illustrated in Fig. 40 it was possible to obtain a range of relative humidities from 20 percent to nearly 80 per cent. Later many tests were made in rooms or special chambers at relative humidities less than 20 percent. All these data indicate that the resistivity of B. coli in air does not decrease very much as the relative humidity decreases below about 35 percent. In fact, the crucial point, if there is any, appears to be at a relative humidity in the neighborhood of 50 percent. Notwithstanding many tests in which the humidity was measured, only general conclusions can be drawn.

Wells [35] has stated that for humid air the exposure necessary to kill 63.2 percent of air-borne B. coli is about ten times as great as for dry air. Rentschler [40] has stated, contrary to findings of other investigators, that high humidity of the air does not increase the resistivity of air-borne bacteria to ultraviolet energy. At least the preponderance of evidence obtained with B. coli indicates that their resistivity is definitely higher at high than at low humidities. The conclusion of the author and his colleagues is that at a relative humidity of 75 percent the resistivity of air-borne B. coli is twice that for a relative humidity of 35 percent for a survival-ratio of 36.8 percent or for 63.2 percent killed. The significance of a survival-ratio of 36.8 percent is discussed in Chapter V.

LETHAL EXPOSURES FOR B. COLI

Certain fundamental principles seem to be sufficiently well established for practical application in the killing of micro-organisms with germicidal energy.

The lethal effect of this energy apparently is not much affected by temperatures ordinarily encountered in ventilating systems and in occupied interiors.

The reciprocity law which is encountered in many avenues of science and technology appears to hold for the killing of bacteria over a wide range of exposures. Specifically applied to this field, this law states that, for a given survival-ratio, the intensity of germicidal energy E multiplied by the time of exposure t is a constant. However, if the exposure is too prolonged, other factors such as growth of organisms or their natural dying rate may submerge the reciprocity law. Other details need not be discussed here.

An exponential law seems to account for the results obtained under practical conditions for any given type of micro-organism. This has been discussed in Chapter V along with various units and terms. This law is reproduced again at this point as a matter of convenience. (See Plate XIV.)

$$\text{Survival-Ratio} = \frac{P}{P_0} = e^{-KEt}$$

where P is the original concentration of bacteria,
P_0 is the concentration after an exposure Et,
K is a constant whose value depends upon the micro-organism and, in the case of air-borne bacteria, depends upon the humidity.

As previously stated, when the exponent e (about 2.718) is minus unity the survival-ratio is $1/e$ or 0.368 and KEt equals unity. The exposure Et corresponding to a survival of 36.8 percent of the original organisms has been termed a *lethe* by Wells.[35] Naturally, new terms are necessary as a new branch of science or technology is developed, but this term does not have much practical value. We have used the term *unit lethal exposure* of the same value. Neither term is fixed quantitatively excepting for a given micro-organism in a given environment. In practice the exposure Et can be expressed in energy measurements and time as microwatt-minutes per sq. cm. or milliwatt-minutes per sq. ft. Some use ergs per sq. cm. One erg per second equals 0.1 microwatt. One microwatt equals 600 ergs per minute.

A practical disadvantage of the lethe or units lethal exposure, as defined in the foregoing, is that it applies to a survival-ratio of 0.368 or a 63.2-percent kill. This is not an attractive practical goal. Unfortunately, complete disinfection is not represented by the foregoing exponential law. Perhaps a survival-ratio of 1 percent or 99-percent kill would be a better level for comparison and discussion. For practical purposes 99.99 percent killed might be considered complete disinfection which would mean sterilization. However, the evolution of specific units and terms will likely be guided by experience and the requirements of practice.

From the many tests and measurements involved in the work of the author and his colleagues[38] it appears that

5 microwatt-minutes per sq. cm. is a fair average value for the lethe or unit lethal exposure for air-borne B. coli when the relative humidity is in the neighborhood of 35 percent. In fact, this value appears to be a practical one for a survival-ratio of 0.368 for relative humidities less than 40 or 50 percent. From approximate data presented by Koller[41] this unit lethal exposure for air-borne B. coli may be estimated to be in the range of 2.6 to 5.8. Wells[35] has given several values varying from less than one microwatt-minute per sq. cm. for dry air to 10 for humid air. Considering the foregoing and the quantity of refined measurements which the author and his colleagues converged upon this point, 5 microwatt-minutes per sq. cm. appears to be a fair value of exposure Et for a 36.8-percent survival of air-borne B. coli for relative humidities less than 40 percent. Actually, indoors the humidity is commonly lower than this during winter months. Therefore, on the basis of the foregoing discussion Table XXI is presented as representing the results of various exposures Et in killing B. coli in air whose relative humidity is 40 percent or less.

From Table XXI it is seen that for a 90-percent kill of B. coli in relatively dry air the exposure should be 11.5 microwatt-minutes per sq. cm. according to the author and his colleagues. For very humid air their results indicate that the exposure should be at least doubled or about 25 microwatt-minutes per sq. cm. For a kill of 99.99 percent in air of 35 percent humidity, the exposure indicated is nearly 50 microwatt-minutes per sq. cm.

Hollaender[36] has presented a table of data, gathered from various sources, in which are listed the exposures to energy of $\lambda 2537$ to inhibit growth of various micro-organisms for 90 percent of the original population. The values of exposure varied from 8300 to 197,000 ergs per

sq. cm. for different organisms listed. These correspond to 13.8 and 328 microwatt-minutes per sq. cm., respectively. The value for B. coli is about 50 microwatt-minutes per sq. cm. However, one must be cautious in interpreting such data. For example, the work with B. coli did not involve

TABLE XXI

Relating Exposure to Survival-Ratio and Percent Killed for B. Coli in Air at Ordinary Temperatures and at Relative Humidities Less Than 40 Percent

Exposure, Et Microwatt-Minutes per Sq. Cm.	*Survival Ratio* P/P_0	*Percentage Killed*
0.5	0.90	10
1.0	.82	18
2.0	.67	33
3.5	.50	50
5.0	.368	63.2
8.0	.20	80
10.0	.135	86.5
11.5	.1	90
15.0	.05	95
19.5	.02	98
23.0	.01	99
26.5	.005	99.5
31.0	.002	99.8
34.5	.001	99.9
46.0	.0001	99.99

exposure of air-borne bacteria. The organisms were exposed on agar surfaces and in one determination were in liquid suspension. The germicidal energy is easily absorbed by various materials. Furthermore, as already indicated, B. coli suspended in water are 5 to 10 times as resistant as they are in air of various humidities. Therefore, in comparing data obtained by various workers, the details of their techniques should be carefully examined. In fact, it is questionable how far results of different investigators can be compared with certainty if they did not use the same conditions and techniques.

NATURALLY INFECTED AIR

There are many kinds of air-borne micro-organisms which vary greatly in resistivity to germicidal energy. The yeasts and molds are generally far more difficult to kill than most pathogenic bacteria. In an industrial process it may be necessary to kill all kinds of air-borne organisms. In such cases, the dosages or exposures for various percentages killed must be much greater than those indicated in Table XXI for air-borne B. coli. For example, it required about 10 times the exposure *Et* to kill 90 percent of the naturally air-borne organisms on petri dishes exposed in certain interiors that it did to kill practically all B. coli exposed on petri dishes. Possibly some of the molds and yeasts are so protected that the germicidal energy cannot penetrate sufficiently to kill them at all. The character of the organism and the degree of disinfection required in a given case are the determining factors in the design of a germicidal installation. (See Plates VI, VIII, IX, XV.)

In the case of pathogens with the possible exception of a few fungi it is a commonly accepted view that they do not vary greatly in their resistivity and that B. coli are fairly representative of these. Assume that the killing of these organisms follows an exponential law over appreciable ranges as indicated in Figs. 36, 37 and in Table XXI, and that germicidal energy is provided in accordance with the resistivity of B. coli and for exposures *Et* that kill 99.99 percent of these organisms. Suppose that the average intensity of germicidal energy *E* is only one-fourth what it should be to kill 99.99 percent of another type of pathogenic organism *X* in the same time *t*. The percentage killed in the latter case will not be merely one-fourth, or 25 percent of the total of the *X* organisms. As seen in Table XXI, 90 percent will be killed. This is commonly considered to

be good practice in some other fields of disinfection. However, the wattage of germicidal sources required for killing 99.99 percent of B. coli is so low that it should often be practicable to increase it many times, particularly in industrial processes.

As indicated in Chapter V, there is evidence that many pathogenic bacteria have apparent resistivities to germicidal energy in the range of one-half to twice that of B. coli. Admittedly the evidence is open to criticism owing to the variety of techniques used by various investigators and to the inadequate measurements of the germicidal energy used. However, by utilizing reasonable factors of safety the data obtained with B. coli provide a guide for design of germicidal installations for killing a high percentage of most pathogens. Recently we have obtained some evidence that certain pathogenic bacteria have a resistivity at least 10 times that of B. coli.

Where it is necessary to kill all or most of the air-borne organisms in connection with products and processes, much higher intensities E of germicidal energy than are indicated by B. coli are necessary for a given time t. However, if t can be increased E can be decreased. The dosage or exposure Et is the key to the solution. For example, in many cases of sterile storage, t is so large that E can actually be relatively small even for highly resistant bacteria. This is also true of many industrial applications. Obviously all applications of germicidal energy must stand the test of results. (See Plate VIII.)

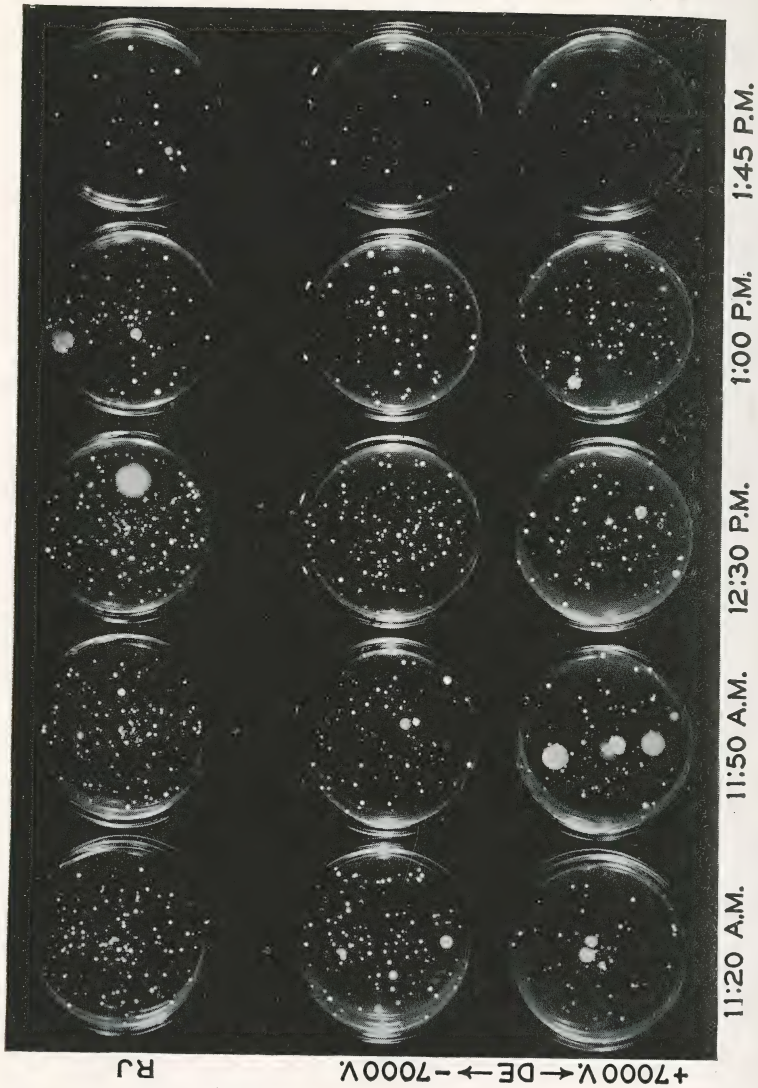


PLATE VII. Showing the effect of the number of occupants in a cafeteria on the concentration of air-borne micro-organisms. The highest occupancy occurs between 11:30 A.M. and 12:30 P.M. Upper row of petri dishes exposed in an RJ air-sampler and the pairs in the lower row in a DE air-sampler.

Infected Communal Air

THERE IS adequate evidence that the communal air in occupied interiors is infected by the occupants. During the ordinary processes of breathing, talking, sneezing and coughing, micro-organisms are expelled from the respiratory tracts into the air—to be breathed again indiscriminately. The occupants by their other activities stir up particles of dust upon which micro-organisms become air-borne. (See Plate VII.) For a half-century much progress has been made in many ways in reducing the spread of diseases by decreasing the transmission of pathogenic organisms through contact, contaminated water and infected foods. A widespread awakening to the hazards of such sources of infection has been achieved. However, only during recent years has there been a widespread awakening to the bacterial contamination of communal air. This does not mean that proper authorities have not recognized air-borne contagion. For example, surgeons, physicians and nurses wear masks for protection of themselves and patients. The important fact is that until the advent of relatively efficient sources of germicidal energy little could be done toward a widespread reduction of air-borne organisms. The availability of means often determines the magnitude of interest in desirable ends. Germicidal energy is unique as a means of killing air-borne bacteria. It not only disinfects the air but does not in itself contaminate the air as is true of other kinds of disinfectants.

With the recent advent of sources of ultraviolet energy of relatively high germicidal efficiency, it was natural that great interest was aroused in investigations in occupied interiors which aimed to determine to what extent the inci-

dence of respiratory diseases could be reduced by irradiating the infected air. Although favorable results of such investigations naturally provide a great stimulus to the use of sources of germicidal energy for this purpose, this is not necessarily the only approach to the problem. In fact, it is only necessary first to prove under laboratory conditions that diseases contracted in, or by way of, the respiratory tract are prevented by killing air-borne organisms or are reduced by disinfecting the air to certain degrees. The second step consists of determining the types and concentrations of pathogenic organisms in communal air. The third step is to determine how to install sources of germicidal energy so as to disinfect the air continuously to any desired degree.

The foregoing procedure is common to many other practices. For example, lighting practice is basically founded largely upon the results of laboratory researches or investigations in which conditions are adequately controlled. This is also true in many medical practices. Confirmatory field investigations are always of interest and value, but in such complex fields as medicine, hygiene and seeing, field investigations can seldom be conducted with ideal controls. However, some extensive pioneering investigations have been under way during the past few years which reveal something of the efficacy of irradiating the air in occupied rooms with adequate installations of efficient sources of germicidal energy. A few glimpses of these are presented before dealing with the more direct and practical approach through determinations of the bacterial content of communal air.

PIONEERING GERMICIDAL INSTALLATIONS

It is beyond the present purpose to deal exhaustively with the effects upon health and hygiene of various successful challenges of the sun by means of artificial sources of radiant energy. A thorough discussion of the ultimate effectiveness of germicidal energy upon the transmission of air-borne contagion is a province of medical and health authorities. However, there are basic foundations and principles of technology in which medical and health authorities are not particularly specialized. These are realms in which the author is particularly concerned. With this explanation a few glimpses of field investigations, conducted or supervised by proper authorities, are presented.

A symposium on aerobiology [37] deals with various aspects of air-borne micro-organisms and their effects. Although many interesting data and discussions are presented, it is obvious that the science of aerobiology is just emerging into an elementary stage. The gaps in knowledge and experience and the need for criteria, devices and techniques are apparent. Likewise, the opportunities for the bacteriologist, physicist and engineer are obvious.

W. F. Wells [43] has pioneered for some time in studies of the results of air-borne disinfection with germicidal energy with encouraging results. Wells, Wells and Wilder [44] have shown that epidemic spread of measles was checked in three irradiated primary schools during an unusually severe epidemic. They irradiated the upper stratum of air in the classrooms. They concluded that "since the dynamic spread of epidemic contagion can be controlled by radiant disinfection of the air, it follows that air must be a vehicle of infection."

Robertson and colleagues [45] conducted extensive investigations in four cubicles, created by suitable partitions, in a hospital with such suitable controls as could be devised. They found that barriers of germicidal energy which screened the openings of the cubicles were effective in preventing the spread of air-borne bacteria from cubicle to

cubicle. In a later paper [46] the results of air-borne infection of babies in the cubicles indicated that twice as many infections occurred among the babies in a control room as in the room equipped with sources of germicidal energy. Experiments involving the irradiation of the upper air in a room occupied by premature infants indicated that when the doors and windows were left closed, the respiratory infections were about half as many as in a similar room in which the upper air was not irradiated.

Sauer, Minsk and Rosenstern [46] have found that barriers of germicidal energy were as effective as actual partitions in preventing cross infections of the respiratory tract in infants. Mundo and McKhann [47] have reported that barriers of germicidal energy appeared to reduce the infections of infants by air-borne bacteria. In all these experiments, the concentrations of air-borne bacteria were markedly reduced by germicidal energy. These uses of screens of germicidal energy are interesting and practicable in many cases. However, for a widespread application of germicidal energy to infected communal air, the irradiation of air in air-ducts, and particularly of air above the occupied zone in interiors, provides a practical solution to the problem of disinfecting air on an extensive scale.

At the U. S. Naval Training Center, Camp Sampson, germicidal lamps were hung from the ceiling of dormitories. These irradiated the upper air. In addition, one source of germicidal energy was installed under every other bunk to irradiate the floor and the dust. Only sleeping quarters were irradiated. Drill quarters, mess halls and other places were not. However, results during the first year [48] indicated a reduction of 25 percent in respiratory illnesses was achieved in those barracks equipped with germicidal lamps. The effect of the germicidal energy in reducing respiratory illnesses was more marked during the early winter months

when the reduction was 35 percent compared with the results in the unirradiated control barracks.

Lurie [49] has shown that rabbits acquired tuberculosis by breathing the air mixed with that exhaled by rabbits which were tubercular. When this air was irradiated with germicidal energy before breathing by the healthy rabbits, they did not acquire tuberculosis.

In these and in other investigations of the bacterial content of communal air, micro-organisms pathogenic to the respiratory tract were found. There is no doubt that air in occupied rooms is a means of transmission of diseases. For example, the types of organisms most commonly found by Mundo and McKhann [47] were staphylococcus aureus, staphylococcus albus, fungi, B. subtilis, B. coli, B. alcaligenes faecelis and occasional diphtheroids and micrococci. Hemolytic streptococci were occasionally found and, at such times, similar organisms were usually recovered from the nasopharynx of patients or personnel throughout the hospital where they conducted extensive investigations. They sampled the air by means of the Wells device involving centrifugal precipitation of bacteria onto a nutrient medium. According to duBuy, Hollaender and Lackey,[50] this device catches only a small percentage of the organisms in the sample of air passed through it. However, notwithstanding this low efficiency in catching air-borne organisms, Mundo and McKhann found the bacterial counts per cubic foot of air were as follows for unirradiated air: Infants' hospital, 18 to 25; Children's medical ward, 35 to 50; Medical outpatient department, 60 to 70; Main operating room, 25 to 30.

In the Infants' hospital the installation of germicidal lamps reduced the bacterial count from 25 to 30 to 3 to 5 per cubic foot. In all cases irradiation of the air by means of germicidal energy markedly, and often greatly, reduced

the concentration of bacteria in the air. Mundo and Mc-Khann made weekly bacterial samplings of the air in the Infants' hospital in the areas in which germicidal lamps were installed and also in the control areas. Fig. 47 has been adapted from their data beginning with December 8 when the germicidal lamps were put into use and continuing

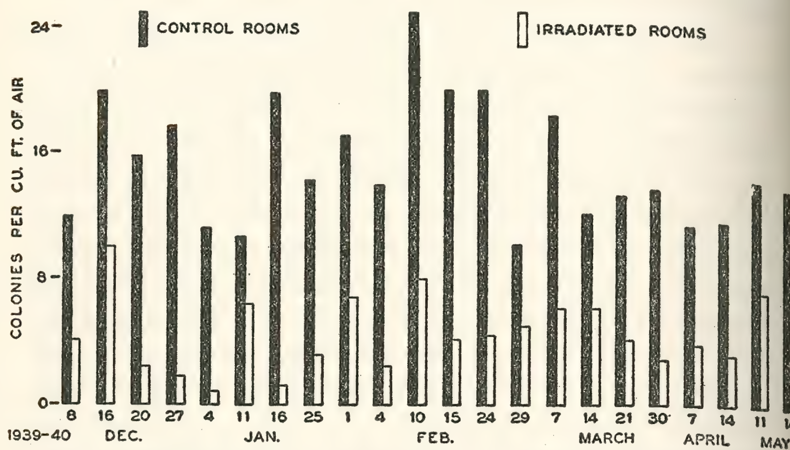


FIG. 47. Relative bacterial content of air in irradiated and unirradiated wards of an Infants' Hospital. (After Mundo and McKhann.)

weekly until May 14, after which the windows and porches were opened. It is seen that irradiation of the communal air markedly reduced the bacterial count. Incidentally, nurses and other personnel wore masks only in the control rooms and not in the rooms irradiated with germicidal energy.

BACTERIAL AIR-SAMPLING

The recent advent of sources of germicidal energy of relatively high efficiency has greatly stimulated interest in air-borne micro-organisms. Naturally, a comparable increase in interest has been stimulated in devices and techniques for catching air-borne organisms in order to

determine their concentration in the air, the contamination contributed by occupants and other possible sources of infection, and the degree of disinfection desired or achieved by a germicidal installation. In brief, a scientific foundation as well as practical measuring devices must be provided for this new technology if it is to be extensively applied.

An inherent difficulty in determining the absolute number of micro-organisms in a given volume of air is the possibility of more than one clinging together. The separation of these clumps has been attempted by bubbling through sterile water and by atomizing air or water in a sampler. From a practical viewpoint, for both laboratory and field investigations, it is desirable to catch the organisms on a suitable culture medium in a petri dish so that they are ready for incubation. In the bubbler devices a measured volume of air is bubbled through sterile distilled water. Then a certain percentage of this water is used to infect a sterile nutrient or culture medium. A refinement of this method designed to break up clumps of organisms involves atomizing the air with sterile water in a closed vessel and then bubbling this misty air through sterile water. However, these techniques are tedious and time-consuming compared with those which employ petri dishes directly. In all cases the infected nutrient is incubated for a given period and the now visible colonies are counted. The various colonies can be separated into additional cultures for the purpose of identifying the various types of micro-organisms.

The nutrient upon which the organisms live and multiply during incubation is of great importance. An ideal nutrient is one upon which all naturally air-borne organisms will thrive. In practice this ideal can only be approached as closely as possible. For sampling air in general, a nutrient used by the author and his colleagues is Tryp-

tose Blood Agar (Difco) and the incubation period was 40 to 48 hours at 37° C. About 45 percent more colonies were countable after 40 to 48 hours of incubation than after only 24 hours. When B. coli were used for artificial infection of air in the laboratory researches, the nutrient used was Levine's Eosin Methylene Blue Agar (Difco). The incubation period was 24 hours at 37° C.

Air-borne bacteria have been impinged directly on a culture medium by gravity, by a blast of air or by centrifugal force. The socalled "open plate" method has been widely used. The heavier particles of dust or moisture to which organisms may be attached will settle upon a horizontal layer of nutrient. By using a petri dish containing a proper nutrient, this sample method is satisfactory if one is chiefly interested in the number of these heavier particles. However, this method is too crude for accurate quantitative determinations of air-borne bacteria. Wells [51] has fairly well eliminated this selectivity in the rate of falling of very small particles by applying centrifugal force. According to duBuy, Hollaender and Lackey,[50] the Wells air-centrifuge catches less than ten percent of the air-borne bacteria passing through it. In fact, this device appeared to catch only a few percent of the bacteria in a given volume of air compared with a bead-bubbler in which air is bubbled through water. It is possible that the latter method separates clumps of bacteria, but this question is still open and plagues those interested in quantitative values.

The author and his colleagues [39] found that with some of the bubbler devices a large percentage of the initial water was lost during the passage of several cubic feet of air. By increasing the height and volume of the air-space shown in the upper part of Fig. 48, the loss of water was reduced to a maximum of a few percent during the sampling of 5 or 10 cu. ft. of air. Therefore, the corrections

necessary when mixing a small measured portion of the infected water with a culture medium in a petri dish were small and the eventual error was relatively small. The disadvantages of making corrections and of transferring a measured portion of the infected water are fairly obvious, particularly when one contemplates making hundreds and even thousands of tests in the laboratory. The disadvantages in field investigations are still greater.

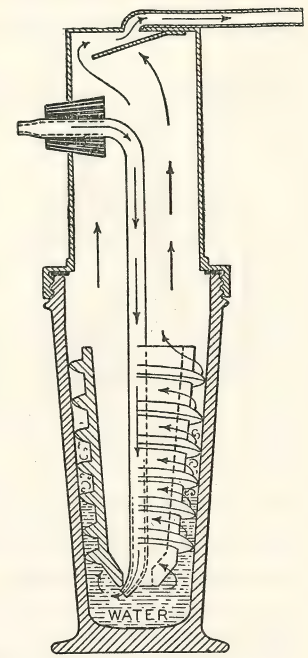


Fig. 48. A wash-bottle converted into a bubbler-type bacterial air-sampler.

An atomizer-bubbler has been described by Moulton, Puck and Lemon [53] in which the infected air is atomized with water and then this misty air is bubbled through water. One aim is to separate clumps of organisms by atomizing the infected air and to collect all, or at least a very large percentage, of them by bubbling through water. The ingenious device, self-contained in one continuous glass enclosure consisting of various parts, has many applications in laboratory researches, but it lacks the simplicity desirable for extensive work and has the disadvantages already noted for field investigations. It was found by duBuy, Hollaender and Lackey [50] that this device caught slightly more air-borne bacteria than the bubblers. It must be borne in mind that if the device must be sterilized after each sampling of air, the time consumed and the inconvenience are prohibitive for extensive use.

One of the simplest types utilizing the principle of impinging the organism directly upon the nutrient in a petri dish has been described by Hollaender and Dalla Valle.[54] In Fig. 49 is illustrated a device of this type which the author and his colleagues[39] have used to some extent. The air enters through a 60-degree glass funnel whose open end is slightly smaller than the petri dish. The best rate of flow of air appears to be about one cubic foot per minute. DuBuy, Hollaender and Lackey[50] found that this device is inefficient compared with bubbler and atomizer-bubbler samplers. The author and his colleagues also found this funnel aeroscope to be inefficient when sampling air artificially infected with B. coli, but found it caught a considerable percentage of naturally air-borne bacteria under certain conditions. In fact, it appears that work with B. coli projected into the air by means of an atomizer may be misleading. Furthermore, the catch of naturally air-borne bacteria may be affected by humidity, electrostatic conditions and other factors.

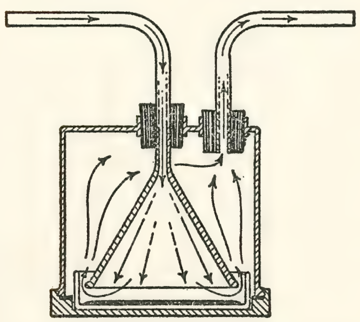


Fig. 49. The so-called funnel aeroscope air-sampler, FA.

EFFECTS OF AN ELECTROSTATIC FIELD

Luckiesh, Holladay and Taylor[52] redesigned the funnel device as illustrated in Fig. 50 and incorporated a DC high-voltage electrostatic field. The petri dish containing the nutrient *N* rests upon a circular metal plate *M* which is one electrode connected to the socket *A*. The funnel is made of metal in order to provide the other electrode which is connected by the arm *C* to socket *B*. With air artificially infected with B. coli by means of an atomizer, it was found that when the electrode under the petri dish is positive, many more B. coli were caught from a given volume of air than when the lower electrode is negative. Apparently this method of atomizing resulted in air-borne B. coli being predominantly associated with a negative charge. This differential effectiveness of positive and negative electrodes in catching B. coli in air artificially infected by means of an atomizer is discussed later.

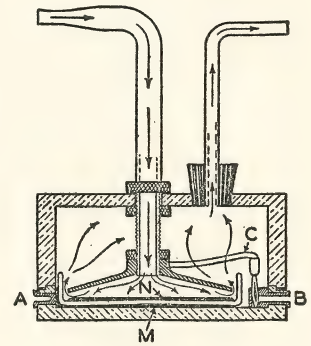


Fig. 50. A modified funnel air-sampler with provision for applying an electrostatic field. *M* and *C* are connected respectively to sockets *A* and *B* in which the terminals of a direct-current high-voltage source may be plugged.

It has been common laboratory practice to infect air in a room with relatively harmless B. coli by means of an atomizer. An improvement over this procedure is to confine the artificially infected air to an infection chamber such as is illustrated in Fig. 51. Considerable experimenting was done with the intake and exhaust in order to obtain and maintain a reasonably constant concentration of B. coli. The height of the chamber is 54 inches and its horizontal cross-section 36 inches by 26 inches. The organisms were injected into the air by means of a Walton atomizer containing a very dilute solution of Heart Infusion Broth infected with Escherichia or B. coli 24 hours old. A small low-speed electric fan was located above the atomizer and below the intake of uninfected air. The air was exhausted outdoors through a pipe with an opening near the bottom

of the chamber. To the outlets at the right various air-samplers could be connected in parallel or in series. A precision gas-meter measured the volume of air passing through the air-samplers at any rate desired. Two germi-

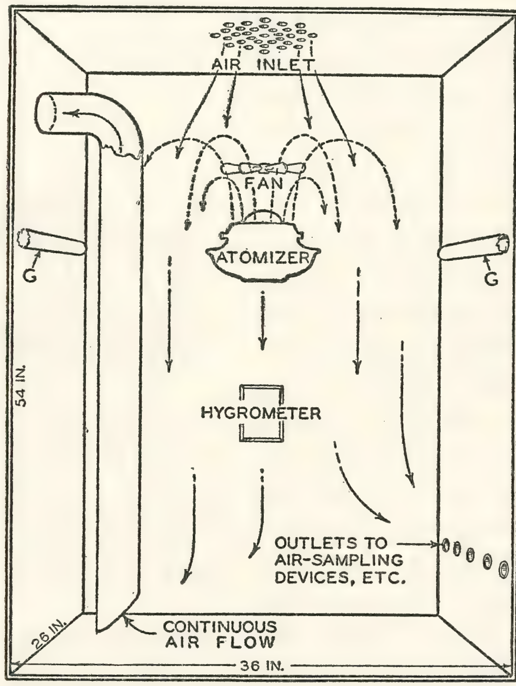


FIG. 51. An infection chamber for artificially infecting the air with B. coli by means of an atomizer.

cidal lamps *G* were installed as shown to disinfect the air and surfaces of the chamber when desired. By experimenting with the ventilation and atomizer, the concentration of air-borne B. coli could be maintained reasonably constant for sufficient periods of time.

In order to study the effect of an electrostatic field, a small tunnel with a rectangular cross-section was con-

structed of insulating plastic (Lucite) and attached to an appropriate outlet from the infection chamber, Fig. 51. A vertical section of this device is illustrated in Fig. 52. This rectangular tunnel was 10 inches long, 4 inches wide, and 1.5 inches high. Metal electrodes, *A* and *B*, could be connected to a DC source of 0 to 8000 volts. Either electrode could be positive or negative as desired. Metal forms with

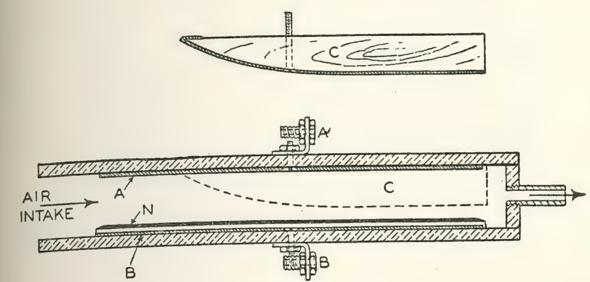


FIG. 52. A rectangular tunnel of transparent plastic for studying the effect of an electrostatic field in bacterial air-sampling. *A* and *B* are electrodes between which a DC high voltage may be impressed. *N* is the nutrient.

vertical sections such as *C* could be placed in the tunnel as shown to constrict the vertical cross-section in various ways for the purpose of altering the velocity of the air as it passed over the glass plate upon which the nutrient *N* had been flowed. The vertical gap between the upper and lower metal electrodes, *A* and *B*, could be varied and *C* could be removed if desired.

Some typical results are illustrated in Fig. 53 of the air-borne B. coli caught when the gap between the electrodes was varied by means of *C* from 1 cm. at the left end (entrance) to 0.5 cm. at the right end (exit). The lower electrode *B* was positive and for the four plates from top to bottom the voltages were 0, 500, 1000 and 2000 volts, respectively. The effectiveness of the electrostatic field is

evident. When such nutrient-coated plates were being exposed with other air-samplers connected in series at the exhaust end of this electrostatic tunnel, relatively few airborne B. coli escaped being caught in the electrostatic

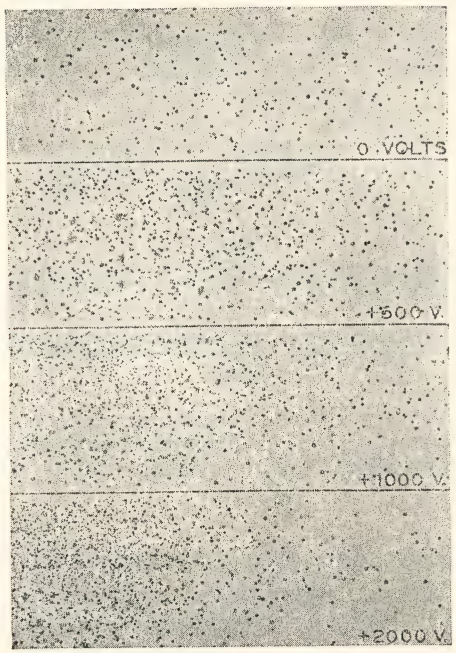


FIG. 53. Illustrating B. coli, in artificially infected air, caught on a culture medium resting on a positively charged plate, illustrated by *B* in Fig. 52. Air-flow was from left to right.

tunnel when the lower electrode was positive and had a potential of +2000 volts or more. Extensive studies were made of the effects and relationships of air-flow, air-speed, voltage, shape and spacing of electrodes. The results were of great value in developing the portable air-samplers described later in which still higher DC voltages are used.

Various studies of the effects of an electrostatic field were made with metal and glass plates coated with a culture medium. The effects are strikingly demonstrated by stretching a metal wire at different distances from a coated plate. The wire and the coated plate were connected to the terminals of a high-voltage rectifier. Voltages ranging from 0 to 8000 volts were used. The maximum concentration of

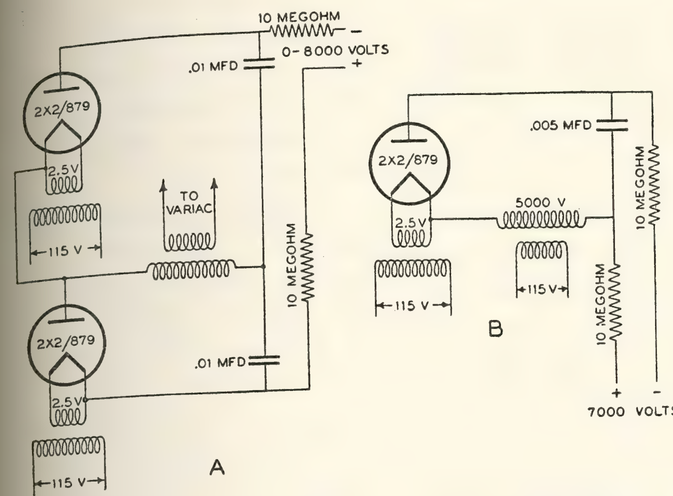


FIG. 54. Wiring diagrams for DC high-voltage rectifiers used in bacterial air-samplers of new designs. A range of 0 to 8000 volts is provided by *A*. Circuit *B* provides 7000 volts.

bacteria was always on the area of the nutrient under and paralleling the wire. When the plate coated with a culture medium was positive, many more B. coli from the artificially infected chamber were caught than when it was negative. This finding was confirmed throughout various tests involving *B. coli introduced into the air by atomization.* However, when collecting air-borne bacteria naturally injected into the air by the occupants of a room, the catch is commonly about the same as when the nutrient plate or petri dish rests on a negatively charged electrode. In other words, for B. coli atomized into the infection chamber

(Fig. 51), a great majority of the organisms apparently are associated with a negative charge, a small minority apparently are associated with a positive charge, and a small percentage appear to be neutral. This evidence aroused suspicion as to some peculiarity of conditions in the infection chamber, but nothing of this sort could be found. Presumably the atomizing produced the condition responsible for the results.

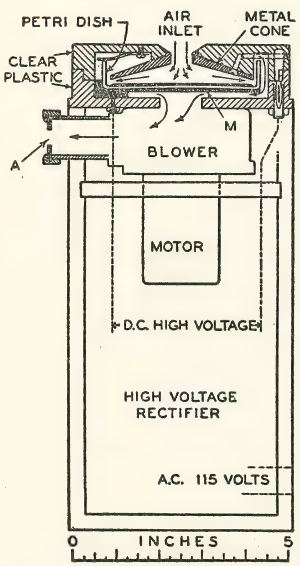


Fig. 55. A vertical section of the Simplex Electrostatic Air-Sampler, SE.

The wiring diagrams for the production of various direct-current high voltages by the rectifier are illustrated in Fig. 54. A DC high-voltage rectifier, built according to the wiring diagram *A* supplies any potential desired within the available range. Two rectifier tubes designated as 2X2/879 were connected as shown. In using these tubes there should be a high insulation between the primary and secondary windings of the transformer. A variable auto-transformer is connected as indicated in order to vary the delivered potential from 0 to 8000 volts. A resistor of 10 megohms is connected in series with each high-voltage terminal to insure safety of the operator. In the electrostatic samplers described later, the wiring diagram illustrated in *B* of Fig. 54 is used. It supplies 0, +7000 or −7000 volts to one of the electrodes in the Simplex Electrostatic sampler (Fig. 55). In the Duplex sampler (Fig. 57) it supplies 0 or +7000 volts to one petri dish and 0 or −7000 volts to the

other petri dish. In each case the metal funnel is connected to the terminal of opposite potential.

SIMPLEX ELECTROSTATIC AIR-SAMPLER, SE

An entirely portable and self-contained electrostatic air-sampler is illustrated in Fig. 55. The high-voltage rectifier is contained in the lower part as indicated. This complete sampler is about 5 inches square and about a foot high and weighs 12 pounds. To distinguish this from another model which contains two air-samplers in parallel, it has been termed a Simplex Electrostatic air-sampler or SE sampler. The forms and dimensions of the upper part containing the petri dish are the result of extensive studies and are drawn to scale. As illustrated by the vertical section in Fig. 55, the upper portion is enclosed with thick clear plastic (Lucite) which has the desirable insulating properties. This plastic enclosure separates about in the middle to insert and remove the petri dish. When this separation takes place, the connection to the right is broken and the high voltage is disconnected. Four narrow flat springs, similar to the one illustrated at the upper left, press downward on the edge of the petri dish, thereby holding it in place. A small blower, installed as shown, draws air in the inlet and discharges it again through the variable aperture *A*. By varying the area of the aperture *A*, various rates of air-flow are obtained. The flow of air through an inlet in the center of the plastic enclosure and squat metal cone is indicated by the arrows. Symmetry in the flow of air is obtained by careful design and construction.

The effectiveness of the electrostatic field is illustrated in Fig. 56. This is a typical series of air-samplings of many made of the air drawn from the infection chamber artificially infected by atomizing B. coli. In this case the

Funnel Aeroscope sampler FA, illustrated in Fig. 49, and the Simplex Electrostatic sampler SE, illustrated in Fig. 55, were connected in series. The petri dishes illustrated in the first two columns were respectively exposed to the arti-

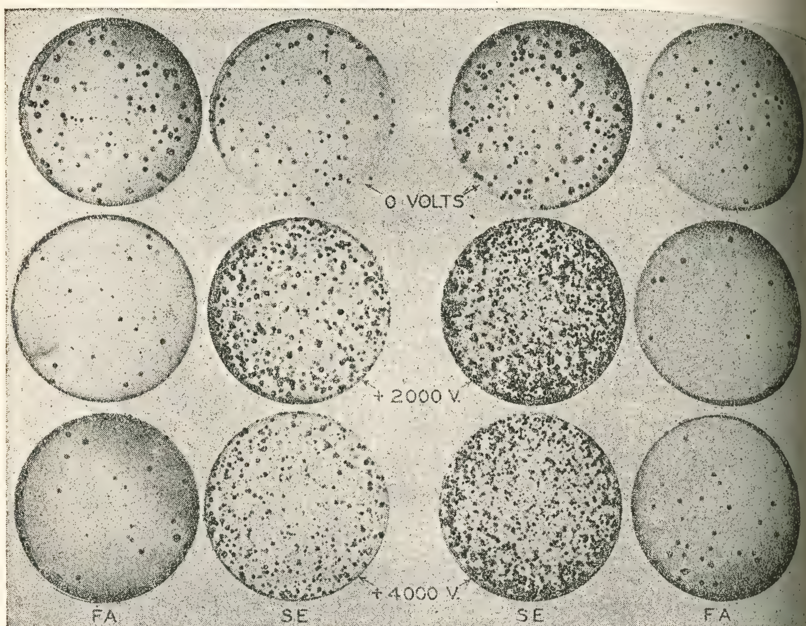


FIG. 56. Colonies of B. coli on petri dishes after incubating 24 hours. In the first two columns are the results obtained with an SE sampler (Fig. 55) in series with, and following, a funnel aeroscope FA (Fig. 49). In the last two columns the SE sampler was in series with and preceded the FA sampler. The effect of the electrostatic field is evident.

ficially infected air passing first through the FA sampler, then through the SE sampler. From top to bottom the electrostatic voltage applied to the electrode under the petri dish of the SE sampler was 0, +2000 and +4000 volts, respectively. The petri dishes illustrated in the last two columns were respectively exposed to air passing first through the SE sampler then through the FA sampler. The concen-

tration of B. coli in the air-sample was not necessarily the same. Otherwise the conditions were the same as they were for the petri dishes illustrated in the first two columns.

The effectiveness of the electrostatic field is obvious from many results such as those illustrated. Many tests of these SE samplers indicate that a rate of air-flow of 0.5 cu. ft. per minute, or even less, is most satisfactory. The best distance between the edge of the upper electrode (metal funnel) and the nutrient in the petri dish appears to be about 3 mm., but there is little difference in the results if this distance is doubled. However, when it is 10 mm., there appears to be a definite decrease in the number of organisms caught. Naturally, the effect of this distance between the metal funnel and the culture medium, which serve as the two high-voltage electrodes, depends upon various other dimensions and also upon the rate of air-flow.

Naturally, the question arises as to the contamination of the air-sampler carrying over from one air-sampling to the following one. After air containing bacteria is drawn through the SE sampler, bacteria deposited on the upper electrode might contaminate the air-samples passed through the sampler subsequently. In order to test this matter, a given volume of air highly contaminated with B. coli was drawn through an SE sampler at the usual rate. The petri dishes were removed and replaced by sterile ones with the usual coating of nutrient. Then completely sterile air was drawn through the sampler. This was repeated many times. In some cases the upper funnel electrode was cleaned with alcohol before drawing through the sample of sterile air. In other cases it was not cleaned. In no case did the number of colonies incubated on the petri dish exposed to the sample of sterile air exceed one thousandth of the number of colonies resulting from the immediately preceding sampling of air highly contaminated with B. coli. Therefore,

by means of this air-sampler many petri dishes may be successively exposed without loss of time, and they are also ready for the incubator.

DUPLEX ELECTROSTATIC AIR-SAMPLER, DE

As these investigations progressed, the efficacy of a powerful electrostatic field appeared to be established, but it was also evident that most of the air-borne B. coli injected into the infection chamber by the atomizer were associated with a negative charge. Space does not permit discussing these aspects in detail.[39] However, it became desirable to construct a Duplex Electrostatic or DE air-sampler so that organisms associated with a positive charge could be caught on one petri dish while simultaneously those associated with a negative charge could be caught on another petri dish. Such a sampler is illustrated in Figs. 57 and 58. The construction of each of two individual samplers is the same as illustrated in Fig. 55. A high-voltage rectifier, whose wiring diagram is illustrated in *B* Fig. 54, is enclosed in the lower part of the case. It supplies both individual units of the DE sampler. The plate upon which one petri dish rests is connected to the positive terminal of the rectifier while the plate upon which the other petri dish rests is connected to the negative terminal of the rectifier. Therefore, when one petri dish is positive, the other is simultaneously negative. The available direct-current potentials are 0 and 7000 volts.

The air enters through the hole ¾ inch in diameter in the center of the plastic enclosure of each unit. One blower serves both samplers. Although the air passages are made identical in both cases, provision is made for adjusting the air-flow through each, so that an equal volume of air is drawn through each of the two units in a given time. After many tests, a rate of 0.5 cu. ft. per minute appeared to be most desirable. Extensive tests showed that, as the rate of

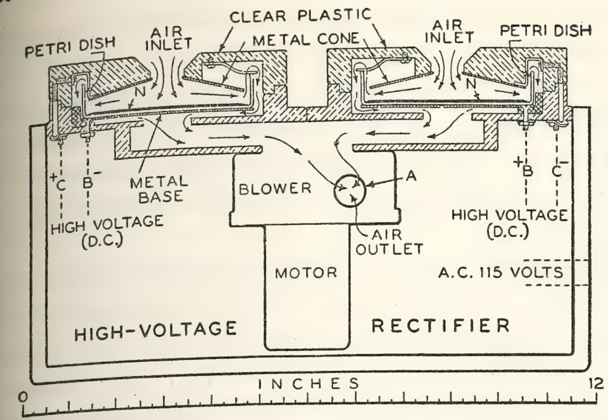


Fig. 57. A vertical section of the Duplex Electrostatic Air-Sampler, DE.

Fig. 58. External view of the Duplex Electrostatic Air-Sampler, DE, which weighs 12 pounds and accommodates standard petri dishes.

air-flow was decreased from 0.9 to 0.3 cu. ft. per minute, the percentage of organisms caught was increased. A rate of air-flow of 0.5 cu. ft. per minute was standardized for the SE sampler and also for each of the two units in the DE sampler. This rate results in a fairly uniform distribution of organisms over the culture medium in the petri dishes.

In general, the results obtained with the DE sampler indicate that the petri dish at −7000 volts catches about the same number of *ordinary air-borne bacteria* as the other petri dish which is connected to +7000 volts. When sampling the *artificially infected air* (B. coli atomized into the air) from the infection chamber (Fig. 51), the negative petri dish caught only about one-fifth as many B. coli as the positive petri dish. As discussed later, the sum of the ordinary air-borne bacteria caught by the two petri dishes of the DE sampler apparently is a high percentage of all the air-borne bacteria in a volume of air equivalent to that passing through either of the two units. Averages from many tests indicate that the DE sampler catches more than 90 percent of all the air-borne bacteria in a given sample of air. However, the results vary considerably and this variation may be due to variations in the physical aspects of the air, such as humidity, which may in turn affect the electrical characteristics of the air and consequently the electrical charges with which the air-borne bacteria are associated.

At any rate, the Duplex Electrostatic air-sampler is efficient, portable and practicable for field work as well as for laboratory investigations.

RADIAL JET AIR-SAMPLER, RJ

During investigations of older methods of air-sampling and developments of new devices, the principle of impinging organisms by mechanical force has also been considered in various ways. The electrostatic principle is an electrical method of achieving this objective to a considerable degree. The advantages of impingement are generally obvious, but there may be disadvantages. The correct answer lies in experimenting with this principle over a considerable range of velocities of the impinging air. After a series of experiments the Radial Jet RJ sampler illustrated in Fig. 59 was developed. It involves a stationary radial slit through which a jet of infected air impinges across the space S on the nutrient N of a petri dish. The petri dish is revolved on a turn-table at a uniform rate of two revolutions per minute by an electric-clock motor. The width of the radial slit varies from 0.16 mm. near the center to 0.47 mm. at its outer extremity. Its length is 41 mm. and its total area is about 14 sq. mm.

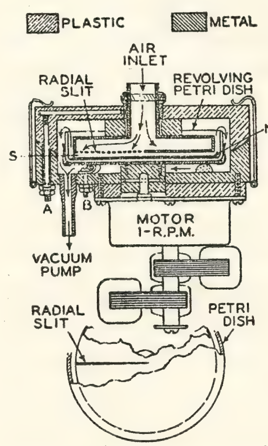


Fig. 59. A vertical section of the Radial Jet Air-Sampler, RJ. At the bottom is a plan view of the radial slit in relation to the revolving petri dish. A DC voltage can be connected to A and B.

The general principles of this device were arrived at without knowledge of the work of Bourdillon, Lidwell and Thomas,[55] and the author and his colleagues[39] designed and tested the air-sampler illustrated in Fig. 59. In the lower part of the illustration is shown a portion of a plan view of the stationary radial slit in relation to the revolving petri dish. The air-flow is illustrated by the arrows. Into this RJ air-sampler an electrostatic field is also incorporated. The parts made of conducting metal and of insulating plastic are indicated by the two types of cross-hatching. The air

enters a metal enclosure whose only outlet is the radial slit. This metal enclosure is one electrode if an electrostatic field is desired. It is electrically connected to *A*, which with *B*, are the connections for the high-voltage rectifier already described in *B* Fig. 54. The petri dish rests on the revolving metal platform which is electrically connected to *B*. The plastic (Lucite) parts are indicated by the broken lines of cross-hatching. In our latest model, three different speeds of revolution of the petri dish are provided to take care of a greater range of concentrations of air-borne organisms.

The vacuum pump which draws air through the narrow radial slit must have a capacity of 1.5 to 2 feet per minute against a pressure drop of not more than 5 cm. of mercury. At a rate of 1 cu. ft. per minute, the velocity of the air in the jet from the radial slit is about 7000 ft. per minute. At a rate of 0.5 cu. ft. per minute, the velocity in the air jet is about 3500 ft. per minute. Thus the infected air impinges at a high velocity upon the culture medium *N* in the revolving petri dish underneath the radial slit. Incidentally, a small centrifugal blower, which is adequate for the Simplex and Duplex electrostatic samplers illustrated in Figs. 55 and 57, does not suffice for the Radial Jet sampler illustrated in Fig. 59. A vacuum pump is necessary and present designs add so much weight and bulk that portability is adversely affected.

This RJ sampler was extensively tested at various rates of air-flow from 1.2 to 0.2 cu. ft. per minute and for various distances *S* traversed by the air-jet before it reaches the nutrient *N* in the petri dish. Owing to variations in the petri dishes a jet-length *S* of about 6 mm. was eventually standardized. The apparent percentages of air-borne organisms and infected particles caught by this air-sampler are very high for the various velocities of the air-jet, when

the electrode on which the petri dish rests is at +5000 volts. When there is no electrostatic field, the apparent percentages caught decrease materially as the rate of air-flow decreases below 0.8 cu. ft. per minute. Obviously, for a constant slit this results in decreased velocities of air in the jet. It was also evident that the length of the air-jet, or the distance *S* in Fig. 59 between the radial slit and the culture medium, is quite important when there is no electrostatic field. Apparently for this Radial Jet sampler the length *S* of the air-jet should be as short as practicable and 3 to 6 mm. appear to be satisfactory. The rate of air-flow was eventually standardized at 1 cu. ft. per minute. At this rate there appears to be no need for an electrostatic field when sampling air naturally infected with air-borne bacteria. Under these conditions and with the nutrient used, the RJ sampler apparently catches at least 98 percent of the naturally air-borne bacteria.

NATURALLY INFECTED AIR

By no means are all the micro-organisms in the air pathogenic to man. Many of them are harmless in this respect, but many of these contaminate food and other products. Furthermore, many of them are much more difficult to kill with germicidal energy than B. coli which are widely used for experimental purposes. For example, the fungi and fungi spores sprayed upon the petri dishes illustrated in Plate VI are much more resistant than B. coli. Most of these were killed in 4 minutes by an intensity of 150 microwatts per sq. cm. of germicidal energy ($\lambda 2537$). This exposure is 600 microwatt-minutes per sq. cm. Practically all B. coli would be killed by an exposure of 100 microwatt-minutes per sq. cm. As seen in Plate VI, some of these fungi and fungi spores resisted exposures of 16 minutes to 150 microwatts per sq. cm. or a total of 2400

microwatt-minutes per sq. cm. Experiments with many petri dishes containing naturally air-borne bacteria collected in a cafeteria during high occupancy indicate that a dosage 10 times that which would kill practically all air-borne B. coli killed only about 90 percent of the naturally air-borne bacteria. In fact, it is quite possible that some fungi and fungi spores may resist very great exposures. Some yeast cells appear to require exposures as great as 50 times that necessary to kill B. coli. (See Plate VI.) However, where adequate time is available, practicable intensities of germicidal energy will kill the bacteria that can be killed by this means. Many applications outside the field of infection of human beings must be studied individually as to the types of bacteria present and their resistivity to germicidal energy. Efficient air-samplers will play important roles in such work, although the simple open-plate method may suffice in many cases.

Progress toward the reduction of air-borne infection must depend upon accurate and efficient air-samplers. The concentration of bacteria in communal air is important as it is in milk and water. If the concentration is greatly reduced by germicidal installations, the chances of infection through air-borne micro-organisms are comparably reduced. Therefore, bacterial air-sampling is of great fundamental and practical interest.

The effect of occupancy on the concentration of bacteria in the communal air is illustrated in Fig. 60 in a cafeteria. Quantitative averages for several days are presented in Fig. 61. The air-borne bacteria arise from the dust which is stirred up and from the respiratory passages of the occupants. Only a few persons are present in this cafeteria before 11:30 A.M. and after 1:00 P.M. The peak of occupancy corresponds with the peak of concentration of air-borne bacteria. These results were obtained with a DE

air-sampler. Each sampling of 5 cu. ft. of air required 10 minutes. Open petri dishes were exposed for 30 minutes each. The maximum number of organisms deposited by gravity on the open petri dishes in 30 minutes was only

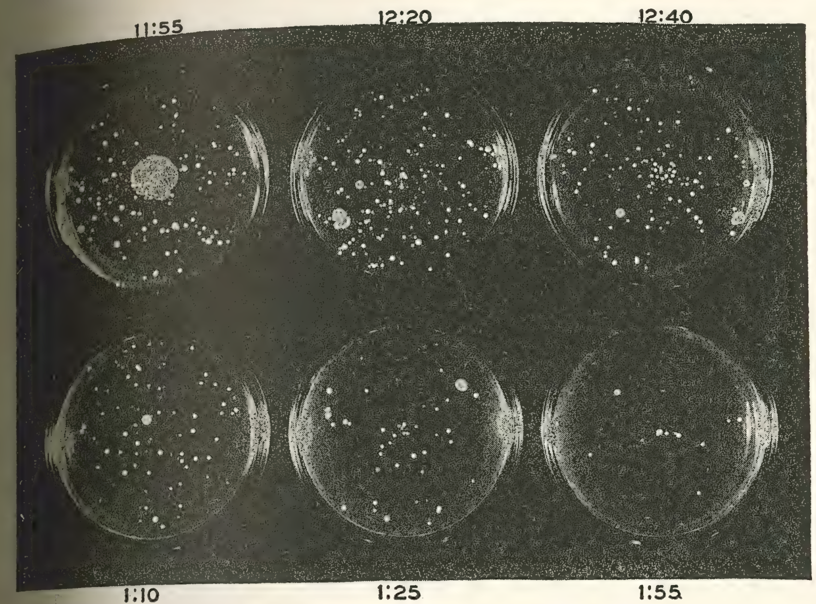


FIG. 60. Petri dishes exposed successively in an RJ sampler to 5 cu. ft. of air in a cafeteria. The period of high occupancy extends from about 11:30 A.M to 1:00 P.M.

about one-third that caught by the DE sampler in 10 minutes. Even in this case of stirred up air and dust, the open dish was only one-sixth as effective as the DE sampler which, according to extensive tests, catches from 80 to 100 percent of the air-borne bacteria, depending upon conditions. If the occupancy remained high for several hours, the concentration of bacteria doubtless would continue to increase beyond the indicated maximum in Fig. 61.

In Fig. 47 it is seen that the concentration of bacteria in a hospital, as determined by an apparently less efficient method, commonly reached 20 organisms per cu. ft. In Fig. 61 it is seen that the concentration of bacteria increased

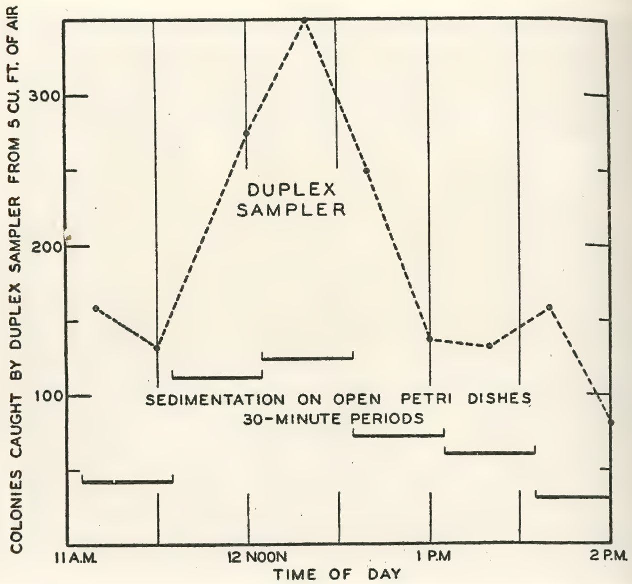


FIG. 61. Showing the variation in the concentration of air-borne organisms in a cafeteria before, during and after the period of high occupancy. The number of organisms caught in 10 minutes with the DC sampler is compared with the number caught by open petri dishes in 30-minute periods.

rapidly to 70 organisms per cu. ft. in less than an hour of the period of high occupancy. In Plate VII typical series of petri dishes (after 48-hour incubation) are illustrated as obtained with a Duplex Electrostatic sampler and a Radial Jet sampler. The decrease in the concentration of air-borne micro-organisms after the period of high occupancy is evident as it is in Figs. 60 and 61.

In Fig. 62 are illustrated two petri dishes exposed in a DE air-sampler to 5 cu. ft. of air in a bedroom occupied by a patient with a severe throat infection. This single occupant of the room coughed and sneezed a great deal. It is seen that the concentration of bacteria in this room of single occupancy is comparable to those illustrated in Fig. 60 and Plate VII obtained in larger interiors with many occupants in average health. The availability of efficient

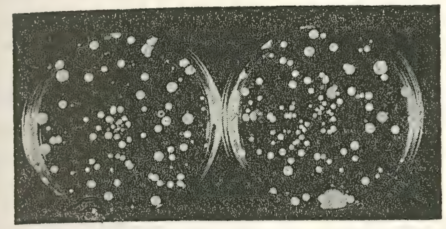


FIG. 62. Petri dishes exposed simultaneously in a DE air-sampler in the bedroom of a patient with a severe throat infection. The bacterial count is comparable with those in crowded interiors.

portable air-samplers which use petri dishes so conveniently should greatly extend the heretofore restricted and relatively crude practice of bacterial air-sampling. (See Plates VII, VIII, XIV, XV.)

Adult human beings at rest breathe about 18 times per minute. The volume of this tidal air is about 20 cu. in. for each breath. Forced inspiration may increase this to 140 cu. in. However, the intake of air for persons sitting in schools, offices, theaters, etc., may be conservatively assumed to be at a rate of 15 cu. ft. per hour. If the concentration of naturally air-borne bacteria is 40 per cu. ft. of air, the intake into the respiratory tracts is 600 per hour or nearly 5000 in an 8-hour day. Many of them accumulate in the nose and throat and some of them and others are forcibly expelled again. Many of these are harmless, but so it

is in the case of milk or water where often the objective is to kill 90 percent of the bacteria originally present. Of course, in the case of milk, much progress has been made in eliminating the source of pathogenic organisms by killing cows. In occupied interiors this means is scarcely practicable for the occupants are the actual sources of most of the infection. From studies of the resistivity of pathogenic organisms, it appears very generally practicable to greatly reduce the concentration of these by irradiating the air with germicidal energy without subjecting the occupants to irritating or harmful dosages.

The results of some extensive bacterial air-samplings in theaters during summer months are of interest. This is the period of best ventilation and of low incidence of respiratory diseases. In one theater, with a large audience and a medium volume of air per person and considerable make-up air admitted from the outside, the concentration of bacteria varied on different days from 25 to 40 organisms per cu. ft. of air. In another theater, with a large audience and a relatively small volume of air per person and with the air cooled and for the most part recirculated, the concentration of bacteria varied on different days from 20 to 50 organisms per cu. ft. of air. In a large theater with a small audience, the concentration of bacteria averaged 10 organisms per cu. ft. of air. In a cafeteria, the maximum concentration of air-borne bacteria on different days varied from 44 to 88 per cu. ft. of air. In a poultry house the concentration of air-borne organisms was found to be 2000 to 4000 per cu. ft. of air.

Buchbinder, Solowey and Solotorovsky [56] have made extensive studies of air-borne streptococci of the alpha hemolytic types. A large majority of these organisms appeared to be of nasopharyngeal origin. These were present most frequently and in greatest numbers in the air of school

buildings, and an apparent relationship was noted between the type of room and degree of occupancy. The largest numbers of these organisms were found in occupied assembly halls and classrooms. The streptococci were also found in subways, theaters and to some extent outdoors along the streets. Although thousands of these organisms were caught by their air-sampler, an average of only 1 or 2 per 10 cu. ft. of air was found in schools, theaters, etc. However, their studies were confined to these specific organisms and the air-sampler they used appears to catch only a small percentage of the total. This illustrates the desirability of using highly efficient samplers so that results of various investigations may be compared quantitatively as well as qualitatively.

Since this work was done, it has come to our notice that Berry [83] has experimented with an electrostatic field in air-sampling devices by means of charged wires. We have also had an opportunity, through private correspondence, to become further acquainted with unpublished work of R. B. Bourdillon and his colleagues.

Disinfecting Air in Occupied Interiors

The past decade has witnessed a change in attitude toward the bacterial content of the communal air in occupied rooms. Bacteriology and its related sciences were in an early stage of development at the turn of the century. Pasteur had been dead only five years. His great work opened the door to scientific studies of bacterial disease and the origin of contagion. Therefore, it is not surprising that epidemiologists as late as 1910 had found little evidence to indicate that diseases were transmitted by air-borne pathogens. One stated, "It will be a great relief to most persons to be freed from the specter of infected air." However, more and more physicians, surgeons and nurses adopted the use of masks over the mouth and nose as a preventive measure. The general attitude toward infected air appears to have been dominated by the idea that pathogens could not remain alive in the air very long, and, therefore, there need be concern only for those expelled from the nose and mouth in close proximity to another person. Furthermore, these forcibly expelled organisms were assumed to be attached to relatively heavy droplets which quickly settled out of the air. In addition, drying was known to kill or attenuate nearly all pathogenic bacteria. However, more detailed investigations with improved techniques have revealed a widespread existence of pathogenic organisms in the communal air of interiors.

The ports of entrance of pathogenic organisms to the human body are known to be the nose and mouth, the digestive tract, the urino-genital tract and the skin and mucous membranes. Some of the pathogens which enter

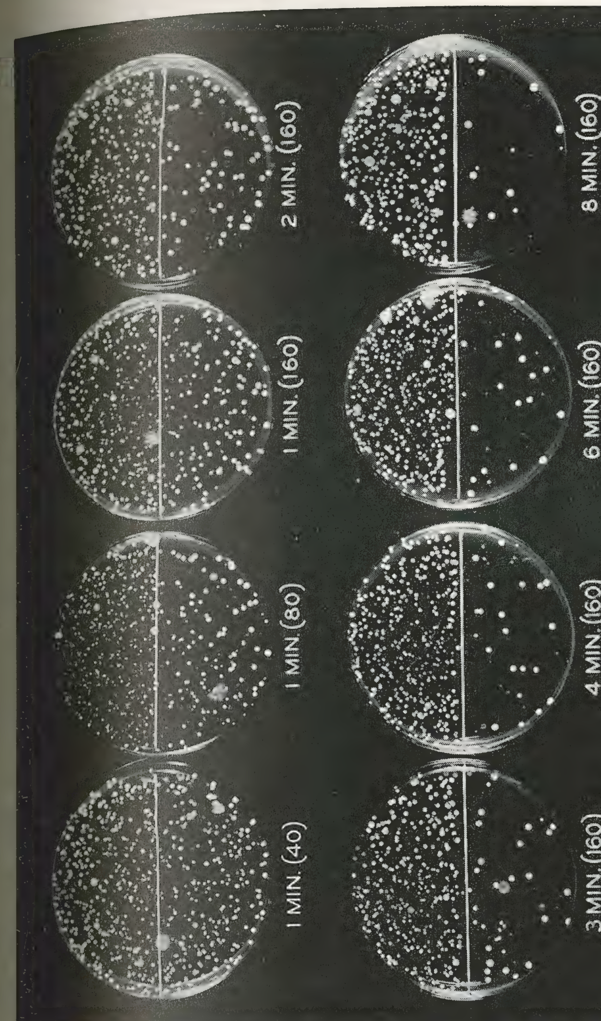


Plate VIII. Petri dishes were exposed for the same period of time to the naturally air-borne micro-organisms in a poultry house. Then the lower half of each was exposed separately, for the number of minutes indicated in each case, to intensities of germicidal flux in microwatts per sq. cm. indicated by the numbers in parentheses. The exposures varied from 40 to 1280 microwatt-minutes per sq. cm.

through the nose and mouth are those causing diphtheria, measles, scarlet fever, mumps, influenza, pneumonia, tuberculosis, septic sore throat, whooping cough and cerebrospinal meningitis. Droplets expelled by the infector may be transmitted to the infectee by direct contact or by inhaling the air-borne organisms. Pioneering germicidal installations, briefly discussed in Chapter VII, already indicate that disinfection of air by means of germicidal energy reduces the incidence of air-borne bacterial disease. Such evidence is difficult to obtain but is mounting and is attracting the attention of more and more bacteriologists, epidemiologists, hygienists, sanitary engineers and various medical authorities.

At the present stage one cannot safely predict the extent to which germicidal installations will be applied to occupied interiors. The most favorable factor, aside from proof of the degree of efficacy in decreasing air-borne contagion, is the high germicidal efficiency of the new sources of germicidal energy. Apparently the concentration of pathogenic bacteria can be reduced to the vanishing point with relatively low wattages. Therefore, operating cost is not likely to deter the use of germicidal energy for disinfecting air. In industrial applications primary incentives will be found in such realms as economics and better products. In occupied rooms, the impelling forces are present in such activities as sanitation and preventive medicine. Proof of economic value may be difficult to establish or to impress upon the public. The community drinking cup lasted a long time after it was condemned. The indictments of communal air are increasing and the disinfection of it is at least, and perhaps inevitably, a refinement of living and working indoors.

The design of germicidal installations for occupied [57] and other interiors quickly becomes simplified, as other

practices do, *after* tedious fundamental researches have provided the necessary foundation for the new technology. The amount of germicidal flux which must be introduced into a given volume of air to maintain a given low concentration of bacteria rather quickly resolves into relationships

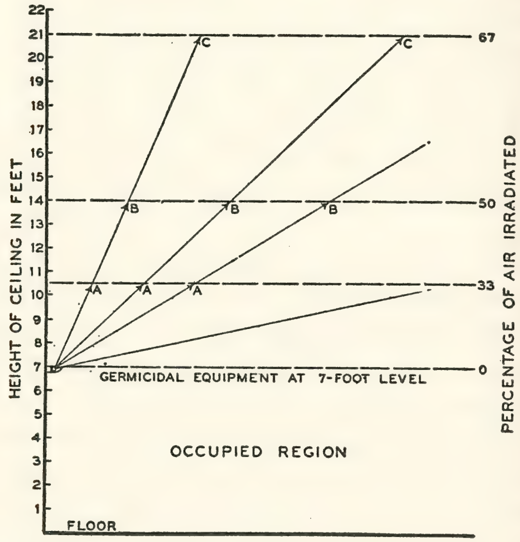


FIG. 63. Showing the effect of ceiling height upon the length of germicidal rays and upon the volume of irradiated air. Efficiency of such an installation increases with the ceiling-height and room-width.

of germicidal milliwatts per sq. ft. of floor area or per cu. ft. of total air in ordinary occupied rooms. Naturally, if occupants are the sources of air-borne infection, there is also a relationship of germicidal milliwatts per occupant. If the upper stratum of air above the 7-foot level, below which is the occupied zone, is used as an irradiation chamber (Fig. 63) the height of the ceiling determines the type of reflector to be used. Of great importance, as seen in Figs. 43 and 45, is the increase in germicidal efficiency of

the installation with the height of the ceiling and the average length of the germicidal "rays" emitted by the germicidal equipment. Also the circulation of infected air from below the 7-foot level to the irradiated space above that level is of great importance.

All these and other factors provide extremely complex problems of bacterial investigations and mathematical computations and correlations. However, before unraveling those complexities for the purposes of understanding the fundamentals and of simplifying the technology of practice, it is well to glimpse some of the limiting factors. The skin and eyes of the occupants must not be subjected to exposures greater than certain low values. Energy in the neighborhood of λ2537 which destroys living organisms also can destroy other living cells and tissues. There is also the matter of killing or damaging plants and of undue fading of materials. Ozone is produced by short-wave ultraviolet energy and its concentration in the air to be breathed by occupants must be kept within bounds. These are glimpses of by-products of germicidal sources which are only partially within the control of the manufacturer of germicidal sources and equipment. They can be controlled to some extent by the designer of germicidal installations.

ERYTHEMA AND CONJUNCTIVITIS

Sufficient exposure *Et* to germicidal energy near λ2537 produces inflammation of the skin (erythema) and of the outer membrane of the eyes (conjunctivitis). According to investigations by the author and his colleagues, the erythemal effectiveness of λ2537 is about 80 percent of the value for λ2967 as shown in Table X and Fig. 30. Other investigators have obtained lower values. However, further work with the new germicidal sources appears to confirm

the higher value for the criterion of barely perceptible erythema as discussed in Chapter III. At any rate, a conservative value of an exposure to λ2537 which produces a minimum perceptible erythema MPE on average untanned white skin is 400 microwatt-minutes per sq. cm. or approximately 400 milliwatt-minutes per sq. ft. This value applies to average untanned skin that is commonly not covered with clothing. For the skin of the inner upper arm, an MPE is produced by exposures as low as 80 microwatt-minutes per sq. cm.

Certain maximum exposures have been tentatively established for the protection of eyes and skin of occupants in a room in which a germicidal installation irradiates the upper stratum of air. For persons exposed for 8 hours daily, the intensity E of germicidal energy on the face and hands is tentatively limited to 0.5 microwatt per sq. cm. This would result in an exposure Et of 240 microwatt-minutes per sq. cm. which is well under the exposure necessary to produce an MPE on average untanned exposed skin. In fact, a continuous exposure to this intensity for 24 hours should not produce an appreciable erythema. However, for persons who might be exposed for 24 hours, such as patients and new-born babies in hospitals, the maximum intensity has been tentatively established in the neighborhood of 0.1 microwatt per sq. cm. The total exposure in 24 hours is 144 microwatt-minutes per sq. cm. If this intensity is doubled, the exposure would be 288 microwatt-minutes per sq. cm. which appears to be well within safe limits for average untanned skin. Patients and babies can easily be screened from much of the germicidal energy reflected from the ceiling. Ordinary glasses completely absorb energy of λ2537.

It is emphasized that these limiting exposures for the eyes and skin are well within that which produces an MPE

on average untanned skin. No harm results from an MPE or from mild erythemas, and the skin adapts itself rather rapidly to this energy. There is some reason for believing that the conjunctiva of the eye has some degree of adaptability which increases its tolerance somewhat. In addition to this, the eyes are apparently somewhat more resistant to erythemal energy than the skin. Sunburn is commonly acquired outdoors without noticeable conjunctivitis.

The occupants of a room can be protected against exposures appreciably greater than the foregoing limits. Properly designed equipment can be so located as to confine the directed germicidal energy to the proper areas. Ceilings and other reflecting surfaces can be painted with a highly absorbing medium. As seen in a later chapter, zinc oxide is outstanding among the white pigments in reflecting little energy in the neighborhood of λ2537. Its absorption-factor for this energy is comparable with black pigments. Experience and knowledge of the various tools and other aspects of this new technology will provide safety to occupants of a room while delivering lethal dosages to the pathogens.

PRODUCTION AND CONCENTRATION OF OZONE

If a low-pressure mercury arc, which is the basis of efficient sources of germicidal energy, were equipped with tubes or bulbs of quartz instead of special glass, this source would emit appreciable energy shorter than λ2000. As hinted in Fig. 26, energy in this region and particularly at about λ1850, decomposes oxygen O_2 with the result that ozone O_3 is produced. This is what happens on a large scale in the upper regions of the atmosphere with the result, as shown in Fig. 10, that the solar spectrum ends rather abruptly near λ2900. The ultraviolet energy of shorter wavelengths emitted by the sun disappears in the production

and absorption of ozone in the high strata of the atmosphere. Some of this ozone reaches the earth by the circulation of the atmosphere. The result is that the concentration of ozone in the atmosphere near the earth's surface is commonly considered to be about 1 part by volume in 100 million. Elford and Van den Ende [58] found it to vary from 0.5 to 4.5 parts in 100 million parts of air. Ozone is relatively unstable and is active in various ways which, combined with the inefficiency of production, account for the low equilibrium concentrations in the atmosphere.

Ozone has various properties, some of which may eventually be desirable by-products of a germicidal installation. At low concentrations it has a pleasant odor reminiscent of clover. To some extent it acts as a deodorant by masking other odors by its own, by its action on the mucous membrane in the olfactory organ, and possibly by partly destroying the odors. It has been recommended as a deodorant where there are odors arising from putrefaction and from such sources as onions and garlic. In high concentrations in the presence of moisture, it kills most disease germs.[58] However, in connection with germicidal installations it is important to limit the equilibrium concentrations of ozone in air to those which can be breathed continuously without irritation or other undesirable effects upon the occupants.

Opinions differ as to the concentrations of ozone that are irritating and otherwise undesirable for breathing. McGuigan [59] states that prolonged inhalation of ozone in concentrations of 200 to 300 parts per 100 million parts of air causes irritation of the mucous membranes of the respiratory tract and pulmonary endema. Thorp [60] in contrasting the toxic properties of air containing pure ozone with those of air containing a mixture of about equal parts of ozone and nitrogen oxides found that pure ozone is non-

toxic in concentrations less than 2000 parts per 100 million of air. The toxic limit for the mixture appeared to be about 100 parts in 100 million. This is of interest in connection with methods which produce ozone accompanied by the nitrogen oxides. Perhaps some of the conflict among opinions as to the desirable limit of concentration of ozone has arisen through this channel.

Reisbeck [61] found from experience with ozone in dwellings and schools that concentrations as high as several parts per 100 million can be tolerated without ill effect. Other investigators recommend much lower values. Witheridge and Yaglou [62] conclude that the safe upper limit of ozone concentration is 4 parts in 100 million for continuous breathing. Doubtless the differences in opinions arise from differences in the criteria employed. Furthermore, anyone who has attempted to measure the concentration of ozone in the air knows that the techniques are tedious and not very accurate.

With the foregoing glimpses of results and conclusions, it is interesting to note that an authoritative medical organization recommends that the concentration of ozone in air for continuous breathing should not exceed 10 parts in 100 million parts of air. This is about 10 times the value commonly accepted for the concentration of ozone in the atmosphere near the earth's surface. It is from 2 to 20 times the values found by Elford and Van den Ende.[58] It is of the order of the most conservative recommendations of other investigators and, therefore, it appears to be a safe value.

The objective in developing a special glass for use as an envelope for the low-pressure mercury arc is to transmit maximal energy in the neighborhood of $\lambda 2537$ with minimal energy of shorter wavelengths, particularly in the neighborhood of $\lambda 1850$ or shorter than $\lambda 2000$. As seen in

Fig. 29 and in a later chapter, the spectral transmission curves of various special glasses do not have an abrupt short-wave cutoff. Therefore, the composition of the glass is a critical matter. This is also true of its thickness. For a standardized composition, significant variations in the production of ozone, due to variations in the thickness of the glass, are found among a group of germicidal sources of otherwise identical characteristics. The amount of ozone can be deliberately increased or decreased by controlling the thickness and composition of the special glass. Although there are some uses and demands for some ozone, let us assume that it is desirable to minimize its production by a germicidal installation.

One of the author's colleagues, L. L. Holladay, made an extensive investigation of the production of ozone by these new germicidal sources with various compositions and thicknesses of glass. He also determined the resulting concentrations of ozone when these lamps were operated in the apparatus illustrated in Fig. 40 and also in closed rooms with and without ventilation. Various 30-watt germicidal sources, otherwise identical, were equipped with tubes of 972 and 974 glass of different thicknesses. For brevity these are reduced to three representative sources. Source *O* had a tube of 972 glass of average thickness. This glass is now obsolete for germicidal sources. Source *S* had a tube of 974 glass of average thickness, which is the standard glass in current use. Source *E* had a tube of 974 glass with exceptionally thin walls. For easy reference the data pertaining to these three 30-watt sources of germicidal energy are assembled in Table XXII. Inasmuch as the production of ozone by a given source decreases considerably during the first 100 hours of operation, the values are averages resulting from various measurements

during this period. Doubtless this decrease in the production of ozone is due to the rapid "solarization" of the glass with the result that the transmission-factor for energy in the region of $\lambda 1850$ rapidly decreases during the first 100 hours of operation. Source *E* initially produced ozone at a great rate, but after a few hours its rate was about twice the average rate of the present standard source *S*.

TABLE XXII

Average Number of Molecules of Ozone Produced per Second by Each 30-Watt Source of Germicidal Energy After the First 100 Hours of Operation

Source	*Glass*	*Watts Emitted Near $\lambda 2537$*	*Molecules of Ozone Produced per Second*
O........	972 aver.	5.4	0.6×10^{16}
S........	974 aver.	8.5	8.4×10^{16}
E........	974 thin	11.0	20.5×10^{16}

Ozone produced in a closed room is decomposed to some extent by energy of $\lambda 2537$ and by surfaces to a slight extent. However, thermal decomposition and ventilation, if there is any, are the chief factors in limiting its concentration in the air. In a small duct 2 feet in diameter and 4 feet long with no ventilation, equilibrium concentrations as high as 50 parts per 100 million were obtained with the standard source *S*. With the highly potent source *E* an equilibrium concentration of 300 parts per 100 million was obtained during the early hours of its operation.

Of more importance are the equilibrium concentrations in a room of ordinary size. These were studied in a room approximately 12 ft. by 18 ft. having a ceiling height of nearly 12 ft. and a volume of about 2500 cu. ft. It could be closed tightly and fresh air could be introduced and exhausted at known rates. Fans stirred the air so that the ozone produced by each of the three representative sources of Table XXII was thoroughly mixed and distributed. Without ventilation the highest equilibrium concentrations

of ozone obtained for sources *O*, *S* and *E* were, respectively, 2, 7 and 12 parts per 100 million parts of air.

The experimental results were combined with computations to produce the series of curves in Fig. 64 which

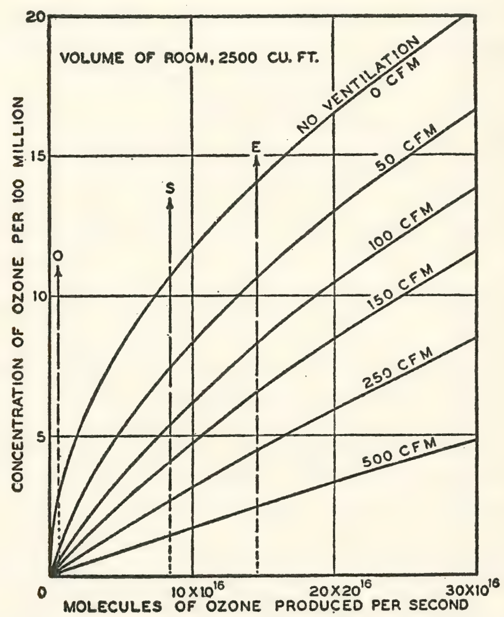


FIG. 64. Equilibrium concentrations of ozone produced in a room by a germicidal source of different potencies in producing ozone. *O*, *S* and *E* are respectively obsolete, standard and exceptionally potent 30-watt germicidal sources.

provide a helpful picture of the effect of ventilation and potency of the source in producing ozone on the equilibrium concentrations of ozone. Sources *O*, *S* and *E* are indicated on the illustration. The various rates of ventilation are expressed in cu. ft. per minute of fresh air admitted at one end of the room and exhausted at the other end. It is seen that insofar as source *S* is representative of 30-watt

germicidal sources that the equilibrium concentrations of ozone are less than 10 parts in 100 million if there is even the slightest ventilation. Fig. 64 also indicates the degree of ventilation necessary if germicidal sources produce ozone much more rapidly than the present standard source *S*. It is emphasized that these results are for one 30-watt source per 2500 cu. ft. of air.

From these results we computed the equilibrium concentrations of ozone for the 18 designs of germicidal installations published elsewhere [57] and discussed briefly later in this chapter. For germicidal sources equivalent to source *S* the ozone concentrations were generally less than 4 parts per 100 million. Even with sources equivalent to source *E* only in one case was the result more than 10 parts per 100 million parts of air.

DAMAGE TO PLANT LIFE

The effect of radiant energy of λ2537 upon plants is discussed in some detail in Chapter XII, but it is touched upon here as a cautionary measure. Plants differ markedly in their resistance to this energy. This is not surprising for short-wave ultraviolet energy is not penetrating and is readily absorbed by most media. The epidermis of various species and parts of plants varies considerably. Damage is a matter of reaching the cells and tissues with this life-destroying energy. Young tomato plants grown indoors are particularly susceptible. In fact, they are generally damaged or destroyed in the lower occupied zone of a room whose upper stratum of air is being irradiated with germicidal energy, without the human occupants experiencing any ill effects.

Continuous exposures as low as 800 microwatt-minutes per sq. cm. damaged young tomato plants. This is only 2 or 3 times that necessary to produce an MPE on average

untanned skin. The minimum exposure which damaged other plants ranged from this value to 50 times this value. This appears to be approximately the same range of resistivity of micro-organisms represented by B. coli, molds and yeasts.

An extensive investigation resulted in the conclusion that the concentration of ozone produced by the germicidal installations was too low to damage tomato plants and the other species tested. In fact, in some cases low concentrations appeared to be beneficial. Concentrations of ozone decidedly greater than one would be content to breathe continuously definitely damaged some of the plants exposed.

FADING OF MATERIALS

The ultraviolet energy accompanying natural and artificial light is not inordinately responsible for fading of materials as is too commonly believed. It is true that the fading power of radiant energy emitted by these sources increases in general as the wavelength decreases, but the increase is not very marked. Such a conclusion cannot be accurately established owing to the countless colors and materials. However, the case is better defined for energy of $\lambda 2537$. As seen in Chapter XI, it generally fades many materials far more rapidly than natural or artificial light. It discolors some plastics and many materials are not immune to it. However, this energy is so readily absorbed that glass affords adequate protection for pictures and other materials. Plastics, varnishes and lacquers also readily absorb it so that protective media can be found where there is urgent need for protection. The reflecting equipment can be so designed that the wall or other surface adjacent to it is not exposed to an excessive intensity of germicidal energy.

SOME BASIC CONSIDERATIONS

The disinfection of air in occupied rooms has for its objective an adequate reduction in the concentration of air-borne pathogenic organisms in the air that is actually breathed by the occupants. In an unventilated occupied room the number of pathogenic organisms in the air increases with time and with the number of occupants. There are two ways of reducing this contamination of the communal air. One is by replacing some of the air by uncontaminated air. Another is to kill these organisms while floating in the air or adhering to the floor, walls and other surfaces. A combination of both methods may be desirable.

As yet there are no accurate correlations between the respiratory diseases resulting from breathing air-borne pathogens and the actual number or concentration of these organisms in the air that is breathed. Perhaps in time such correlations may become available, but for the present it is necessary to approach the matter in other ways. The simplest approach is to reduce the concentration of pathogenic organisms in the air as much as is practicable as is done with water and milk. If adequate window area were available and this could be open to the outdoors, as is practicable during midsummer, there would be no problem of contaminated air. But this is not possible during many months of the year outside the tropical regions. Furthermore, most interiors when closed do not have ventilating systems with the capacity necessary to keep the concentration of air-borne organisms as low as it is in the summertime with the windows open. In fact, in a room of high occupancy it is impracticable to provide a sufficient rate of decontamination by actual air-replacement.

By exposing the communal air to a sufficient intensity of germicidal energy for a sufficient time, the resulting dis-

infection of the air is equivalent to a similar reduction in bacterial content by actually replacing a sufficiently large volume of infected air with fresh air from outdoors.[35,63] In general, it appears that a practicable system of air-disinfection involves a reasonable ventilation for the primary purposes of reducing odors and the concentration of carbon dioxide, to which is added a system of air-disinfection in the room itself. There are many variations in conditions, but the actual killing of air-borne organisms in the occupied room appears to have possibilities that are practically unrealizable by ventilating systems which actually replace contaminated air with fresh air at a certain continuous rate.

Let us assume that an installation of germicidal lamps has been operating long enough for the average concentration of bacteria in an occupied room to arrive at a constant value of P_0 per cu. ft. of air. Under this condition each of the M occupants of the room is assumed to expel an average of B bacteria per minute. Obviously, when equilibrium has been reached, the rate of killing by means of germicidal energy equals the rate at which the occupants M are expelling live bacteria into the air. One criterion by which the performance of an air-disinfection installation may be judged is the ratio P_0/B.

In ordinary ventilating practice a given volume of air, with its content of bacteria, is withdrawn from the room each minute and replaced by an equal volume of fresh air which may be assumed to be germ-free. In the case of disinfection by means of germicidal energy, the lethal flux kills a given number of bacteria each minute without removing the air from the room. The *equivalent air-replacement* V is the volume in cu. ft. of air that would have to be removed and replaced each minute in order to remove bacteria at the same rate as they are killed by germicidal energy. For a room with M occupants there must be a

given volume of either actual or equivalent air-replacement per minute per person V/M in order to maintain a satisfactory low concentration of bacteria in the room.

Thus two criteria, P_0/B and V/M, are available. The first is direct and explicit. It is the relative average concentration of bacteria in the air after equilibrium has been established. The second is indirect and referable to ventilation performance from the viewpoint of air-borne organisms. As criteria there is no choice between them for one is the reciprocal of the other.

There are two other criteria by which an installation might be appraised. One is the total equivalent air-replacement V in cu. ft. per minute, and the other is the number of equivalent air-changes V/V_0 per minute, where V_0 is the volume of the room. If these quantities are to become completely satisfactory, the number of occupants M must be taken into account and also the average contribution of undesirable bacteria by each occupant. The number of equivalent air-changes per hour is $60\ V/V_0$. In Tables XXIII–XXV it is seen that it is practicable to obtain 100 and even 200 equivalent air-changes per hour by actually killing the air-borne pathogens by irradiating the upper stratum of air in occupied rooms.

One of the basic factors affecting the efficiency of disinfection of the air in an occupied room is the circulation of air. Means must be found for rating this factor in any given case in terms of the character and degree of the circulation which may be natural or artificial or both. If there were little or no circulation of air in the room, practically all the bacteria in the irradiated stratum (Fig. 63) would be killed while the air in the unirradiated occupied stratum would be laden with living organisms. Under these conditions the efficacy of the disinfecting installation would be practically zero for the reason that the *circulation-factor*

would be practically zero. Thus a new term is necessary for basic practical considerations of air-disinfection by means of sources of germicidal energy installed in occupied rooms. (See Fig. 65.)

If the air in a room circulated at such a rate that the concentration of bacteria in all parts of the room were

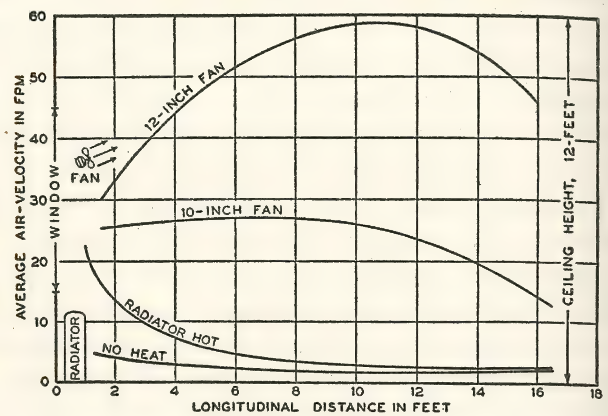


FIG. 65. Average air-velocities in a closed unventilated unoccupied room for four conditions.

practically uniform, a suitable germicidal installation would be maximally effective. In such a case the circulation-factor would be practically unity. This new factor C could be defined as the ratio of the relative concentration of bacteria (or number per cubic foot of air) for an infinite velocity of air (perfect mixing) to the relative concentration of bacteria, P_0/B, for a finite velocity of air. It could also be defined as the ratio of the equivalent air-replacement V for a finite velocity of air to the equivalent air-replacement for a perfect mixing of the infected and disinfected air in the room.

Admittedly, it is difficult to describe the circulation-factor for it represents a resultant of an infinite variety of

velocities, directions and magnitudes of air-currents in an occupied room. It is less difficult to comprehend and it can be described in terms of ultimate results of a germicidal installation. In Fig. 66 circulation-factor C is plotted against units of lethal exposure KEt per cycle of air movement.

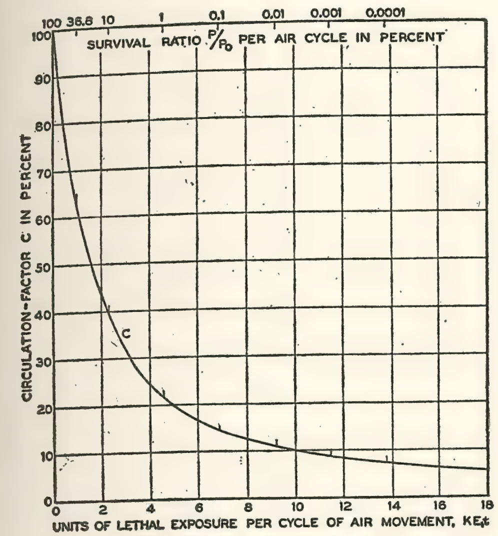


FIG. 66. The relation of the circulation-factor C of air to the units of lethal exposure KE_tt per cycle of air-movement.

ment. This makes the curve generally useful instead of merely illustrative. The scale of survival-ratios at the top of Fig. 66 is related to exposure as shown in Table XXI and Fig. 67. We standardized, for computational purposes, a unit lethal exposure at 4.75 milliwatt-minutes per sq. ft. for B. coli in air at normal temperatures and with a relative humidity of 35 percent. The unit lethal exposure for B. coli is less than the foregoing value for lower relative humidities which are common indoors in winter. It is greater for very humid air but this aspect needs further study.

In Fig. 67 the unbroken line indicates the relationship between exposure Et in milliwatt-minutes per sq. ft. and

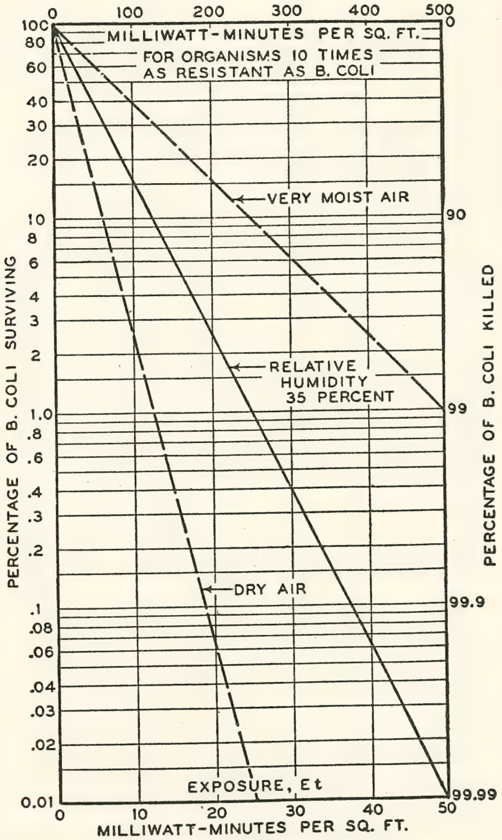


FIG. 67. Showing the exponential relationship of exposure in milliwatt-minutes per sq. ft. and survival-ratio of B. coli or percentage killed for air of 35-percent relative humidity. The possible limits for dry and very moist air are also indicated.

survival-ratio and percent killed for air-borne B. coli in air of approximately 35 percent relative humidity. For simplicity it is plotted for an exposure of 50 milliwatt-minutes

per sq. ft. for a nearly complete kill (99.99 percent), instead of the slightly lower value given in Table XXI. The broken lines indicate the probable range from very dry air to very moist air. The limits have not been well established, but it is believed the unbroken line in Fig. 67 is fairly conservative for air-borne B. coli in interiors during the cold season when the relative humidities indoors are commonly less than 35 percent.

The upper scale in Fig. 67 is for micro-organisms 10 times as resistant to germicidal energy as B. coli. It is obvious that the values of Et in the upper scale are 10 times those in the lower scale. Thus Fig. 67 can represent the relationship between exposure Et and percent killed for bacteria of any degree of resistivity by properly increasing the values of the lower scale.

IRRADIATING THE UPPER STRATUM OF AIR

A simple and obvious method of disinfecting communal air in an occupied room involves exposing the upper stratum of air to germicidal energy.[35, 57, 64] If the sources of germicidal energy are located at a level of 7 feet above the floor and are screened from the occupants, the upper stratum of air can be disinfected to a high degree in a short period of time. Efficient reflectors are available for the purpose. Aluminum whose surface has been specially treated is a very efficient reflector of energy of $\lambda 2537$. The reflection-factors of the upper walls and ceiling for this energy must be low enough so that the intensity of germicidal energy reaching the eyes and skin of the occupants is insufficient to cause conjunctivitis or severe erythema. As discussed in Chapter V, these low intensities may have some therapeutic value as indicated by work on the prevention and cure of rickets.[22, 42] Materials having high or low reflection-factor are available as seen in a later chapter.

Fig. 63 illustrates some basic principles of disinfecting air in an occupied room by exposing the upper stratum of air to germicidal energy. As seen in Chapter VI the effectiveness of a germicidal source of energy increases with the size of the air-duct. This is also true when the upper part of a room is the irradiation chamber. The efficacy of a source of germicidal energy depends upon the length of the path before the energy reaches an absorbing surface, such as the walls and ceiling. Assuming the sources to be installed at the 7-foot level as in Fig. 63, it is obvious that the length of most of the germicidal rays increases as the height of the ceiling increases. For a low ceiling the rays indicated by *A* are relatively short. For a higher ceiling the rays *B* are longer. For a high ceiling the rays *C* are still longer. At the right of the illustration is a simple scale indicating the volume of irradiated air in terms of the total air in the room. It is obvious that the distribution of germicidal energy by the reflecting equipment should differ for different heights of ceiling. The reflectors should generally project the energy in directions having strong horizontal components. This is increasingly important as the ceiling height decreases. Appropriate reflecting equipment is available for these various requirements as illustrated in Fig. 73.

The difference between disinfecting a surface and a volume of air is very important. Suppose a surface 1 sq. ft. in area is infected with B. coli and held perpendicular to one of the rays illustrated in Fig. 63. Suppose it is at such a distance that the intensity of germicidal energy is 50 milliwatts per sq. ft. As seen in Fig. 67, under certain conditions 90 percent of the B. coli would be killed in 15 seconds, 99 percent in one-half minute and 99.99 percent in one minute. However, the germicidal energy would be almost com-

pletely absorbed by the surface and, therefore, is no longer available for further use.

Now replace this surface with an imaginary thin film of air one foot square. The same degrees of killing would take place in the corresponding periods of time, but *no significant amount of the germicidal energy would be absorbed*. This energy would pass on to the next layer of air and do the same killing. In other words, the killing of the B. coli on the square foot thin film of air would be repeated throughout a cubic foot of air and so on throughout the volume of air that energy traversed. Of course, there would be a diminution of intensity of energy due to the operation of the inverse-square law. However, in most of the larger well-designed installations germicidal energy from other directions adds reinforcements. Actually, in designing for spatial disinfection of air, the average length of the germicidal rays *R* and average intensity *E* of germicidal energy are dealt with. Then the matter of time is taken into account. The result is average exposure *Et*. Thus we arrive at the very important matter of average air-velocity (Fig. 65) and the number of cycles of air-movement per minute or per hour to and from the irradiated stratum. Fig. 66 now assumes more significance.

In an actual installation the germicidal flux F_0 emitted by the longitudinal source may be considered to be emitted in elementary wedges from equipment with an efficiency *U*. The total flux emitted is UF_0 or *F*. If the germicidal flux traverses a volume of *V* cubic feet through a distance *R* in feet in a parallel or divergent beam, the average flux density or intensity of germicidal flux *E* is FR/V milliwatts per sq. ft. In an actual occupied room germicidal flux is absorbed by the walls and ceiling. The average effect may be allowed for by a factor Z which is termed

the wall-factor. Therefore, the average flux density E_1 in milliwatts per sq. ft. in the irradiated space of V_1 cu. ft. is

$$E_1 = FRZ/V_1$$

where F is the total flux entering the irradiated space and R is the average length of the germicidal rays in feet. The wall-factor Z in occupied rooms should approximate unity.

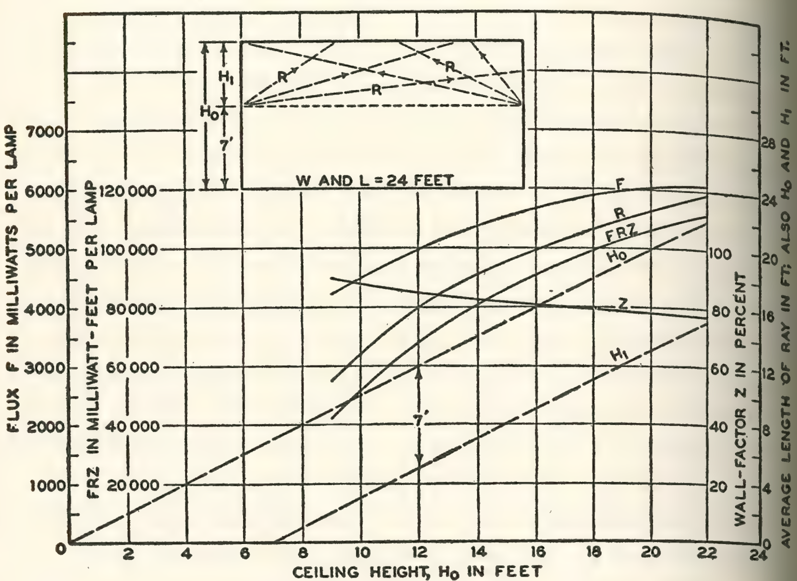


FIG. 68. The effect of ceiling height upon certain factors when the stratum of air above the 7-foot level is irradiated by four standard 30-watt germicidal sources.

The results of mathematical treatment of these various factors are illustrated in Fig. 68 for a room 24 ft. by 24 ft. with a ceiling height H_0 and a vertical height H_1 of the irradiated stratum above the 7-foot level. It is seen that the lethal flux F emitted by the germicidal equipment and its efficiency U increase with the ceiling height. This is merely a matter of requiring a less concentrating reflector

for a greater ceiling height for a room of fixed width and length. The average length of the germicidal rays R and the milliwatt-feet FRZ per lamp increase with the ceiling height. Study of the effects of ceiling height on these factors reveals basic principles involved which affect the efficiency of germicidal installations. The circulation of air, which is exceedingly important, is illustrated in Fig. 65 for a closed unventilated room and discussed later.

Extensive data obtained with controlled air, as described in Chapter VI, provide the basic facts, and mathematics provides the means for predicting the results which can be obtained in ducts, in other enclosed spaces, and in occupied rooms. Sufficient experimental data were also obtained in actual rooms with air artificially infected with B. coli. These basic data on the rate and degree of disinfection and on the intensity and distribution of germicidal energy have been used by Buttolph [64] as the basis for practice. Wells has also published valuable data in a series of excellent papers.[35, 43, 63] Here we shall draw from our own work [38, 39, 57] for illustrations of the principles involved and the results obtained.

In Fig. 69 are illustrated typical results of bacterial samplings in a closed room and under conditions described later. The room was 14 ft. × 18 ft. with a ceiling height of nearly 12 ft. and a volume of 2500 cu. ft. The upper three petri dishes reveal colonies of B. coli (after 24-hour incubation) taken from the air when it was not irradiated with germicidal energy. The lower three petri dishes reveal an almost complete killing of the air-borne B. coli by two 30-watt germicidal sources located at the 7-foot level as illustrated in Fig. 63. One source was located at each of the opposite ends of the room. The initial output of each source was 11,000 milliwatts of energy of λ2537. The average in-

tensity of germicidal energy throughout most of the irradiated space averaged about 50 milliwatts per sq. ft. From Table XXI and Fig. 67 it is seen that this intensity results in an almost complete kill of air-borne B. coli in one minute.

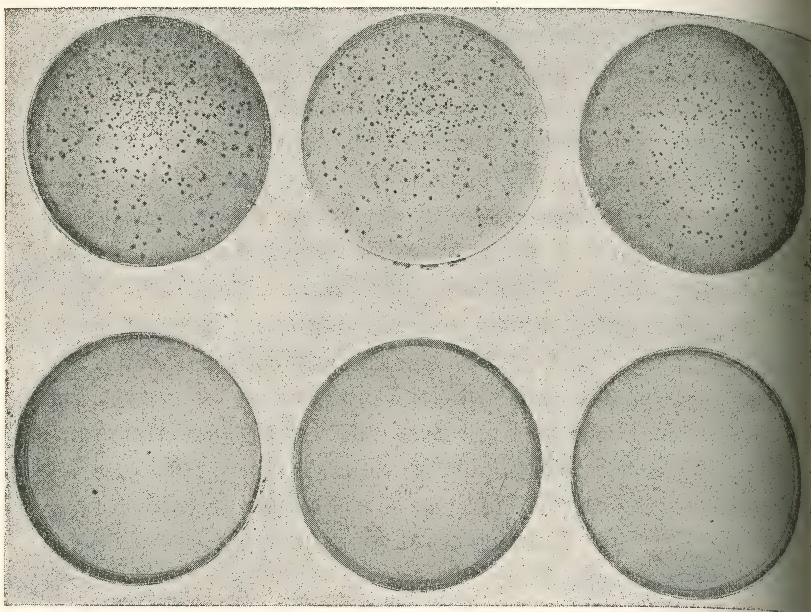


FIG. 69. The top row illustrates colonies developed on petri dishes exposed to a given sample of air infected with B. coli. Petri dishes in the lower row were similarly exposed to air which was being irradiated with germicidal energy.

If the air circulated so that on the average it remained in the irradiated space one minute, the kill would be 99.99 percent. In one-half minute, the kill would be 99 percent. For organisms of higher resistivity, either E or t or both must be increased accordingly. The results illustrated in Fig. 69 were obtained with the heat radiators turned on and the 12-inch fan in operation as described in the following section. With less circulation of air, more B. coli survived as was evidenced by the bacterial samplings. (See Plates VIII, XIV, XV.)

CIRCULATION OF AIR

If there were no circulation of air in rooms illustrated in Figs. 63 and 70, disinfection of the upper stratum of air would be of no value to the occupants. However, there are air-currents even in closed unventilated rooms due to differences in temperature just as there are breezes and winds outdoors on a larger scale due to the same causes. Convection currents rise from hot radiators. They rise vertically and force replacement from upper to lower strata. Less noticeable currents rise from the heating due to each occupant. Air cooled by cold windows tumbles downward. Artificial light-sources cause convection currents. Activities of occupants stir the air. To all these contributors to air-movement fans can be added. If there is a ventilating system it increases the circulation.

It has been necessary to study these air-currents in actual rooms in which the movement of air is controlled by air-replacement from ducts and in rooms in which the movement of air is due to circulating fans, movement of occupants or merely differences in temperature. The average velocity of air in a room varies from a very low value to about 10 feet per minute when it is due to actual air-replacement. The velocities otherwise obtained may vary from a very low value to the limit of comfort of the occupants. Apparently the lowest velocities of air which are definitely noticeable by persons normally clothed and somewhat active are of the order of 60 to 100 feet per minute.

In a closed unventilated unoccupied room 14 ft. by 18 ft. with a 12-foot ceiling with the steam radiators turned off, air velocities were found to vary from 1 to 7 FPM.

With the radiators in operation the velocities ranged as high as 35 FPM. By adding an ordinary electric fan, placed overhead on a wall and directing the air-stream slightly above the horizontal, the velocities ranged from 25 to 100 FPM. The average velocity of the air in feet per minute over the entire room was 2.5 with no heat and no fan; 6 with heat and no fan; 25 with heat and 10-inch fan; and 50 with heat and 12-inch fan. The average air-velocities produced along the length of the room by each of the four different conditions are illustrated in Fig. 65. Inasmuch as the velocity of air is a very important factor in disinfecting air by irradiating the upper stratum, much consideration should be given to it. Hot radiators and cold windows produce powerful air-currents, but fans and planned ventilation can contribute much to the effectiveness of these germicidal installations.

Let us consider a room with a ceiling height of 14 feet in which the vertical depth of irradiated air is 7 feet. The volume of the upper stratum of air above the 7-foot level would be equal to that of the lower occupied stratum of infected air which is not irradiated. Suppose that the circulation is similar to that illustrated in Fig. 70 and suppose that the air rises over one-half of the room at a uniform rate of 60 ft. per minute or one foot per second. Obviously, over the other half of the room it would be descending at the same average rate. In 7 seconds one-half of the lower stratum would be replaced by an equal volume of disinfected air from the upper stratum. In 14 seconds one complete air-change would take place. This is at a rate of about 4 air-cycles per minute or 240 per hour. An air-velocity of 60 feet per minute is apparently not very objectionable to occupants if they are normally clothed and somewhat active. A vertical velocity of air of 35 ft. per minute would result in about 120 air-cycles per hour. If infected air is

replaced at this rate by disinfected air from the upper stratum, the equivalent of excellent *sanitary* ventilation would be achieved. Compare this with 6 to 12 air-changes per hour which are not always attained with mechanical ventilation.

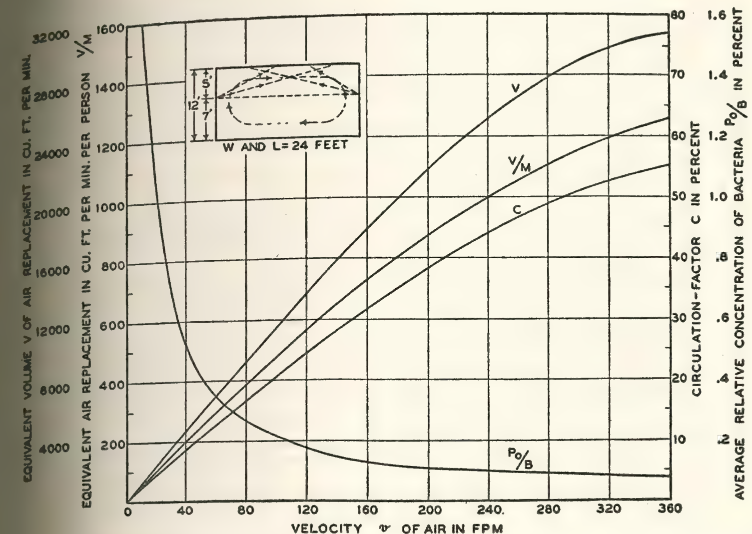


FIG. 70. Showing the variation of air-disinfection with the rate of air-movement in a room 24 ft. × 24 ft. with a 12-foot ceiling and 24 occupants. The air above the 7-foot level is irradiated by four standard 30-watt germicidal sources.

This type of circulation is illustrated in Fig. 70 for a room 24 ft. × 24 ft. with a 12-foot ceiling and 25 occupants. The upper 5-foot stratum of air is assumed to be irradiated with four 30-watt germicidal sources, each of which initially emitted 11,000 milliwatts in the spectral region of λ2537. The efficiency of the reflectors is 63 percent. As the average air-velocity increases from a low value to 100 FPM, it is seen that P_0/B decreases rapidly to a value of 0.2 percent. This means that the number of bacteria B per cu. ft.

is only 0.2 percent of the number expelled per minute per occupant. It is assumed that the bacteria have the same resistivity as B. coli. It is interesting to note the values of C are less than 25 percent for average air-velocities less than 120 FPM. In this range the equivalent air-replacement per

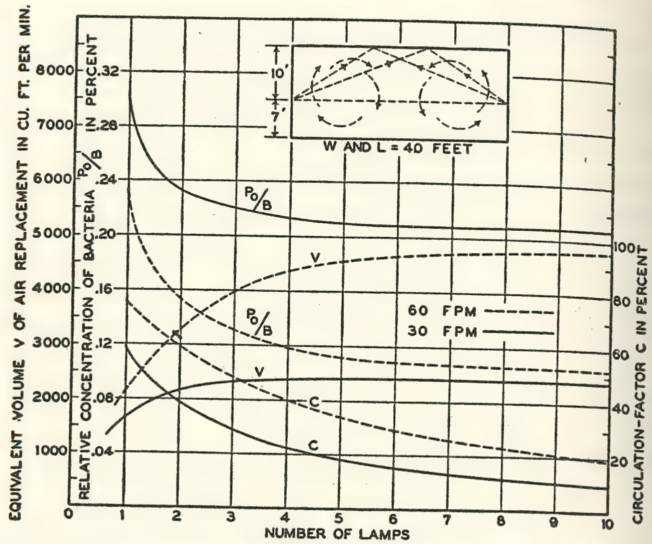


FIG. 71. The interdependence of the number of standard 30-watt germicidal sources and the velocity of air-movement. Only the air above the 7-foot level is irradiated.

occupant ranges up to 580 CFM. Compare this with a rate of 30 CFM per occupant supplied by mechanical ventilation in schools. Within the range of air-velocities from 0 to 120 FPM, the equivalent air-replacement ranges up to about 13,800 CFM. The volume of this room being 6912 cu. ft., this value means about 2 air-change equivalents per minute or 120 per hour. This rate is about 20 times that provided by mechanical ventilation in schools and about 10 times that which is commonly provided by excellent mechanical ventilation.

In Fig. 71 the computed results are plotted for a room 40 ft. × 40 ft. with a 17-foot ceiling and 50 occupants. The 30-watt germicidal sources, varying in number from 1 to 10, were assumed to be located at the 7-foot level in appropriate reflectors. The data are plotted for two average air-velocities, 30 and 60 FPM. It is seen that with air moving at 60 FPM, one germicidal source is as effective as two sources with the air moving at 30 FPM. With four or more germicidal sources, the equivalent air-replacement is about twice as great for an average air-velocity of 60 FPM as for 30 FPM.

VARIOUS GERMICIDAL INSTALLATIONS

In preceding sections the basic factors have been discussed for installations of germicidal sources at the 7-foot level in occupied rooms. In order to illustrate further the relationships of the various factors and of the results obtained, 18 installations for rooms of various sizes are presented and analyzed. The computations are based on the following assumptions and conditions:

a. The relative humidity of the air was 35 percent.
b. The infecting micro-organisms were equivalent to B. coli in resistivity or susceptibility to radiant energy of λ2537.
c. The survival-ratio of bacteria, and percentage killed, follow the exponential law discussed in Chapter V and illustrated in Table XXI and Fig. 67.
d. The unit lethal exposure is 4.75 milliwatt-minutes per sq. ft. This means that 63.2 percent of the bacteria are killed by this exposure.
e. Each 30-watt germicidal source emits 11,000 milliwatts in the spectral region of λ2537, but the efficiency of the reflectors varies in accordance with requirements.
f. No factors of safety are introduced to take care of depreciation of the reflecting equipment due to dust or decrease in the output of the germicidal sources.
g. With the exception of Designs 14 and 15, the irradiated space was that above the 7-foot level and, therefore, the dominant direction of the germicidal rays was horizontal.
h. The average velocities of air in the irradiated space varied from 48 to 80 FPM, which are within practical limits of comfort and achievement.

The results of the computations are presented in Tables XXIII, XXIV and XXV along with the results achieved. Detailed study of these reveals many interesting facts and

TABLE XXIII

Essential Details of Six Designs of Germicidal Installations in Rooms of Various Dimensions and the Results Achieved in Each Case for Bacteria Equivalent to B. Coli

Design Number		*1*	*2*	*3*	*4*	*5*	*6*
Length of room in ft.	L	24	24	24	24	24	30
Width of room in ft.	W	24	24	24	24	24	30
Ceiling height in ft.	H_0	9	12	17	22	12	12
Depth of irradiated stratum in ft.	H_1	2	5	10	15	5	5
Volume of room in cu. ft.	V_0	5,180	6,910	9,790	12,670	6,910	10,800
Volume of irradiated stratum in cu. ft.	V_1	1,150	2,880	5,760	8,640	2,880	4,500
Milliwatts emitted by each source	F_0	11,000	11,000	11,000	11,000	11,000	11,000
Milliwatts emitted by each unit.	F	4,200	5,000	5,800	6,100	5,000	4,840
Efficiency of reflecting unit F/F_0, percent	U	38	45	53	56	45	44
Average length of ray in ft.	R	11	16	20.6	23.8	16	18.3
Ratio of ray length to room width, percent	r	46	67	86	99	67	61
Wall-factor in percent	Z	90	85	80	77	85	83
Milliwatt-feet per lamp	FRZ	42,000	68,000	96,000	112,000	68,000	73,500
No. of 30-watt germicidal lamps.	N	4	4	4	4	3	4
Average flux density in irradiated space in milliwatts per sq. ft.	E	146	94.4	66.7	51.9	70.9	65.3
Velocity of air in irradiated space, ft. per min.	v	48	48	48	48	72	60
Time air is exposed to flux in one circuit of room, min.	t	0.5	0.5	0.5	0.5	0.33	0.5
Units of lethal exposure per air cycle	KE_1t	15.4	9.94	7.01	5.46	4.97	6.87
Survival ratio after irradiation	P/P_0	0.0000	0.0000	0.0009	0.0043	0.0069	0.0010
Circulation-factor, percent	C	6.5	10.1	14.3	18.3	20	14.5
Number of occupants	M	25	25	25	25	25	40
Equivalent air-replacement							
Total cu. ft.	V	2,300	5,760	11,500	17,450	8,580	9,000
Per occupant, cu. ft. per min.	V/M	92	230	460	698	343	225
Per occupant, cu. ft. per hr.	$60V/M$	5,520	13,800	27,600	41,880	20,580	13,500
Per cu. ft. of room	V/V_0	0.44	0.83	1.17	1.38	1.24	0.83
Air-change equivalents per hr.	ACE	26	50	70	83	74	50
Relative concentration of bacteria, percent	P_0/B	1.1	0.43	0.22	0.14	0.29	0.44

relationships. A few of these are emphasized briefly in the comments which follow.

Data from Designs 1 to 4 are plotted in Figs. 68 and 70 where the air is assumed to make a more or less complete circuit of the room. In large rooms having widths and

lengths of 60 ft. or more, the air was assumed to rise at the sides and to descend in the center of the room, or vice versa, as illustrated in Fig. 71.

In Designs 1 to 4 it is seen that the efficiency of the reflector increases from 38 to 56 percent as the height of

TABLE XXIV

Details of Designs of Germicidal Installations and the Results Achieved

Design Number		*7*	*8*	*9*	*10*	*11*	*12*
Length of room in ft.	L	12	16	40	60	120	120
Width of room in ft.	W	12	16	40	60	60	60
Ceiling height in ft.	H_0	12	12	12	12	30	40
Depth of irradiated stratum in ft.	H_1	5	5	5	5	20	30
Volume of room in cu. ft.	V_0	1,728	3,070	19,200	43,200	216,000	288,000
Volume of irradiated stratum in cu. ft.	V_1	720	1,280	8,000	18,000	144,000	216,000
Milliwatt-feet per lamp	FRZ	50,500	58,400	88,400	98,000	217,000	283,000
No. of 30-watt germicidal lamps	N	1	1	6	10	14	24
Average flux density in irradiated space in milliwatts per sq. ft.	E_1	70.1	45.3	66.3	54.4	21.1	31.4
Velocity of air in irradiated space, ft. per min.	v	48	48	72	72	80	80
Units of lethal exposure per air cycle	KEt	3.69	3.18	7.76	4.78	2.22	3.73
Circulation-factor, percent	C	26.4	30.3	15.1	20.7	40	26.1
Number of occupants	M	2	4	50	100	1,000	1,000
Equivalent air replacement							
Total cu. ft.	V	2,810	3,680	14,400	42,800	257,000	375,000
Per occupant, cu. ft. per min.	V/M	1,405	920	288	428	257	375
Per occupant, cu. ft. per hr.	$60V/M$	84,300	55,200	17,280	25,680	15,420	22,500
Per cu. ft. of room	V/V_0	1.63	1.2	0.75	0.99	1.19	1.30
Air-change equivalents per hr.	ACE	98	72	45	59	72	78
Relative concentration of bacteria, percent	P_0/B	0.07	0.11	0.35	0.23	0.39	0.27

the room and height of the irradiated stratum increases from 2 to 15 feet. This is due to the fact that the reflector can be less concentrating as these heights increase.

It is apparent in Designs 1 to 13 that occupied rooms with low ceilings are more difficult to disinfect than rooms with high ceilings. The increase in the effectiveness of 4 germicidal sources is illustrated in Designs 1 to 4 for the same size of room and same number of occupants, but with increasing height of ceiling and irradiated stratum. Note the increase in equivalent air-replacement. The air-change

equivalents ACE per hour for Designs 1 to 4 increased from 26 to 83. The equivalent air-replacement per occupant increased from 92 to about 700 CFM.

Designs 13, 14 and 15 deal with a building with a gable roof such as on army barracks. In Designs 14 and 15 it was

TABLE XXV

Details of Designs of Germicidal Installations and the Results Achieved

Design Number		*13*	*14*	*15*	*16*	*17*	*18*
Length of room in ft.	L	100	100	100	200	200	200
Width of room in ft.	W	20	20	20	100	100	100
Ceiling height in ft.	H_0	7–11	7–11	7–11	25	25	18
Depth of irradiated stratum in ft.	H_1	0–4	H_0	H_0	15	15	10
Volume of room in cu. ft.	V_0	18,000	18,000	18,000	500,000	500,000	360,000
Volume of irradiated stratum in cu. ft.	V_1	4,000	7,400	6,200	300,000	300,000	200,000
Milliwatt-feet per lamp	FRZ	43,800	64,200	57,000	261,000	261,000	210,000
No. of 30-watt germicidal lamps	N	8	8	12	40	40	25
Average flux density in irradiated space in milliwatts per sq. ft.	E_1	87.6	69.4	110	34.8	34.8	26.2
Velocity of air in irradiated space, ft. per min.	v	60	60	60	60	100	100
Units of lethal exposure per air cycle	KE_1t	4.61	2.44	3.87	6.10	3.66	2.76
Circulation-factor, percent	C	21.5	37.4	25.3	16.4	26.6	34
Number of occupants	M	100	50	100	1,000	1,000	1,000
Equivalent air replacement							
Total cu. ft.	V	15,850	40,500	36,400	360,000	585,000	375,000
Per occupant, cu. ft. per min.	V/M	158	810	364	360	585	375
Per occupant, cu. ft. per hr.	$60V/M$	9,480	48,600	21,840	21,600	35,100	22,500
Per cu. ft. of room	V/V_0	0.88	2.25	2.02	0.72	1.17	1.04
Air-change equivalents per hr.	ACE	53	135	121	43	70	62
Relative concentration of bacteria, percent	P_0/B	0.63	0.12	0.27	0.28	0.17	0.27

assumed that the germicidal energy was directed downward in the center of the room and that the air-currents rose at the sides and descended in the center of the room. This could be accomplished by means of fans and could be aided by hot radiators at the sides of the room.

Design 18 deals with an industrial interior with a monitor roof.

It is emphasized that no factors of safety are included for these installations. The output of these germicidal

sources decreases during their useful life and the output of sources and reflecting equipment decreases appreciably if they are not kept clean. Through neglect the intensity of germicidal energy in the irradiated space might decrease 50 percent. However, this does not mean a 50-percent decrease in the number of bacteria killed. It is seen in Fig. 67 that this would mean a decrease from 99.99 to 99 percent killed, or from 99 to 90 percent killed. Nevertheless, a reasonable factor of safety is advisable to allow for the probable variation in the resistivity of pathogenic organisms. At lower relative humidities than 35 percent, the resistivity of B. coli decreases. If this is true of other organisms, the commonly low humidity indoors in winter appears to provide a factor of safety.

SANITARY VENTILATION BY AIR-CHANGE EQUIVALENTS

The disinfection of air by actually killing the air-borne pathogenic organisms creates a new kind of ventilation which may be termed *sanitary ventilation.* In the past, ventilation has been considered from the viewpoints of body odor and the concentration of carbon dioxide. The latter is not harmful, but it is a measure of the contamination of the air by the occupants. If the average number of pathogenic organisms expelled by an occupant were as well known as is the amount of carbon dioxide exhaled, the concentration of carbon dioxide might also be a measure of the needs of sanitary ventilation.

Mechanical ventilation by actual air-replacement has been generally considered to be reasonably satisfactory when a sufficient volume of air is supplied to a room to keep the concentration of carbon dioxide below 10 parts in 10,000 parts of air. This requires a supply of fresh air at a rate of 20 to 50 CFM per occupant. Compare this with the rates of 92 to 1400 CFM of equivalent air-replacement per

occupant in Tables XXIII, XXIV and XXV achieved by disinfecting the air in the occupied rooms.

Suppose fresh air is supplied by mechanical ventilation at a rate of 33 CFM per occupant in a classroom 20 ft. × 40 ft., with a 10-foot ceiling and 24 occupants. Thus 2000 cu. ft. of fresh air would be supplied per occupant, or a total for the 24 occupants of 48,000 cu. ft. per hour. The volume of the room is 8000 cu. ft. Therefore, the actual replacement would be 6 air-changes per hour. The dilution of the contaminated air with fresh air follows an exponential law if there is perfect mixing. At the end of the first 10 minutes 8000 cu. ft. of fresh air will have been admitted. Assuming a complete mixing of the fresh and contaminated air, 36.8 percent of the original air still remains in the room. At the end of 20 minutes 13.5 percent of the original air remains. At the end of 30 minutes 3 air-changes had taken place and about 10 percent of the original air still remains in the room. It would require 90 minutes for 9 air-changes with the result that 99.99 percent of the original air had been taken from the room by mechanical ventilation.

Now let us consider the bacterial content of the air in the foregoing case. After the occupants had left the classroom, it would require 30 minutes for 3 air-changes which, through dilution with fresh air, have rid the room of 90 percent of the original air-borne bacteria. It would require 9 air-changes and 90 minutes to rid the air of 99.99 percent of the original bacteria. A germicidal installation can accomplish this in a very short time with proper circulation of air within the room. If the occupants had remained in the room, they would have been expelling bacteria into the room at some average rate. A germicidal installation can readily provide 60, 100 or 120 air-change equivalents ACE per hour as is seen in Tables XXIII, XXIV and XXV. Mechanical ventilation can be used to supply 6 to 10 air-

changes per hour to get rid of body odors and to keep the concentration of carbon dioxide down to permissible values. Sanitary ventilation can provide many times more air-change equivalents to keep the concentration of pathogens to the exceedingly low values indicated in the foregoing tables.

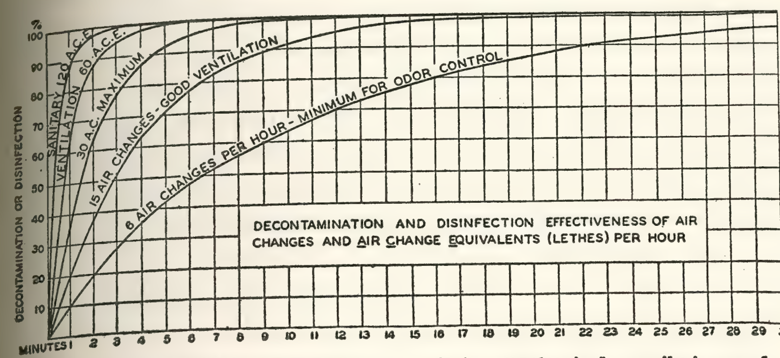


Fig. 72. Rates of decontamination of air by mechanical ventilation and of disinfection by germicidal energy.

In Fig. 72 are plotted [64] the actual air-changes and results achieved or achievable during 30 minutes by mechanical ventilation. What is commonly considered good ventilation provides 10 to 15 air-changes per hour. The possibilities of disinfection of air are illustrated by 60 and 120 air-change equivalents ACE per hour or units of lethal exposure (lethes) per hour.

Irradiating the air in a ventilating system while it is flowing in air-ducts may be sufficient for sanitary ventilation of rooms of low occupancy. However, this method of disinfection has the limitations of mechanical ventilation. Therefore, to obtain an almost complete killing of air-borne pathogens, or a high degree of sanitary ventilation, it is necessary to irradiate the air in the occupied room as discussed in this chapter.

SIMPLIFIED DESIGN OF GERMICIDAL INSTALLATIONS

From results such as are described in this and preceding chapters, it has become possible to simplify the design of germicidal installations. A 30-watt source, supplying a given milliwatts of germicidal flux, can be related to a given height and volume of irradiated space. Equipment which properly reflects and distributes the germicidal flux for a given case can readily be obtained or designed. Typical distributions of available equipment are illustrated in Fig. 73 as determined by Buttolph.[64] By multiplying watts per sq. ft. by 1000, milliwatts per sq. ft. are obtained. Figs. 74 and 75 are also borrowed from Buttolph to show the intensities of germicidal flux at various distances from a typical fixture containing a 30-watt germicidal source.

In Fig. 74 are shown the iso-intensity curves in the vertical plane with one fixture on one wall and another on the opposite wall of a room 32 ft. long or wide. It is seen that, for a 12-foot ceiling, the intensities throughout the vertical plane are generally greater than 25 milliwatts per sq. ft. From Fig. 67 it is seen that this intensity operating for one minute kills more than 99 percent of air-borne B. coli. Considerable volumes of the irradiated space have intensities which kill 99.9 percent in one minute.

These facts are confirmed by Fig. 75 which shows the iso-intensity curves of the two fixtures in the plane of the tube and in the direction of maximum intensity.

Tables XXIII, XXIV and XXV deal with such a variety of cases that the number of 30-watt germicidal sources for almost any occupied room can be estimated fairly accurately. However, guided by these and other data and by experience, Buttolph has reduced the specification of germicidal sources and equipment to simple tables. As the practice of sanitary ventilation develops, bacterial air-

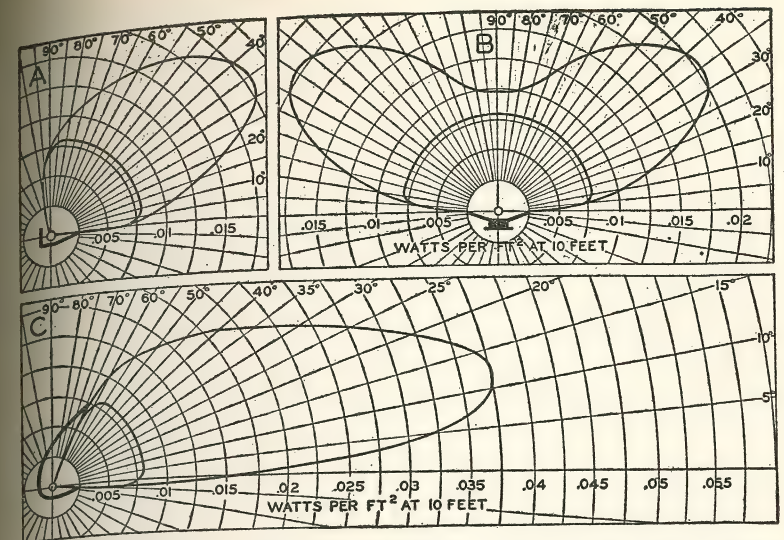


FIG. 73. Typical distributions of germicidal energy in the vertical plane perpendicular to the tubular 30-watt source.

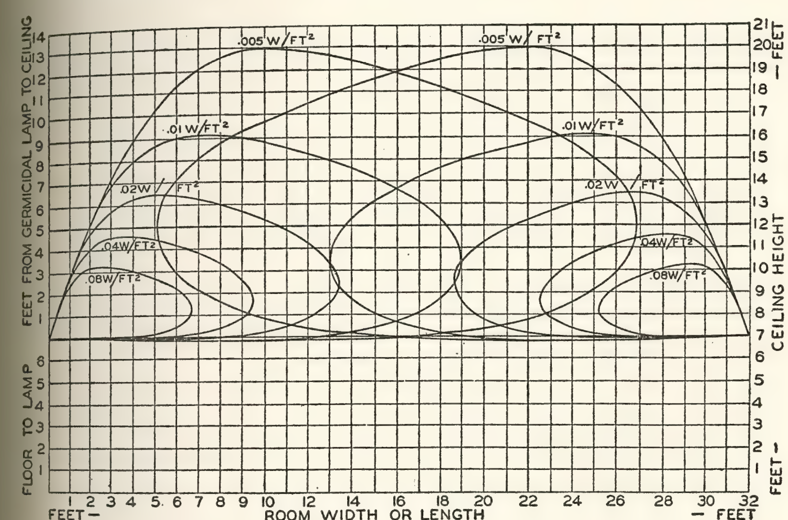


FIG. 74. Iso-intensity curves in the vertical plane for two typical germicidal fixtures, each containing a standard 30-watt source. See *A* and *C* in Fig. 73. (After L. J. Buttolph.[64])

sampling will determine the possibilities of further refining and simplifying the use of germicidal energy for disinfecting air.

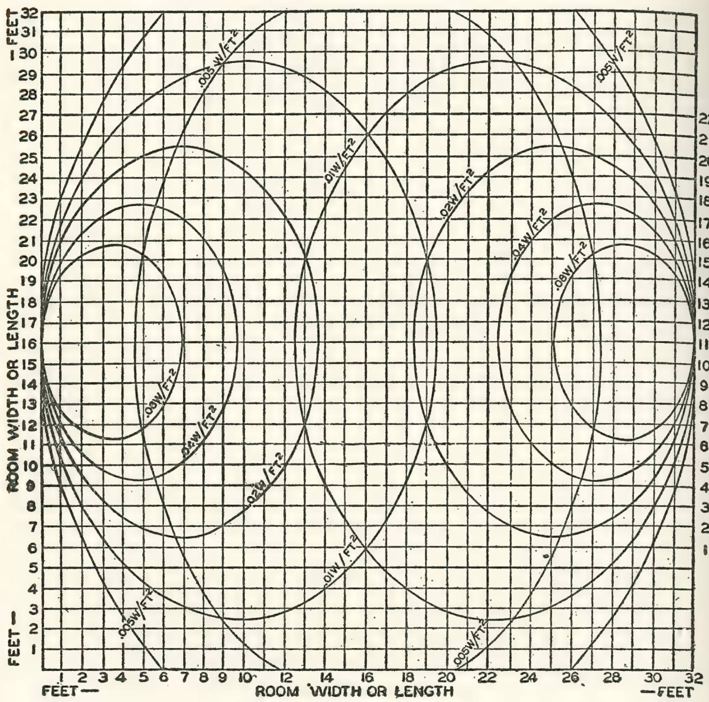


FIG. 75. Iso-intensity curves in the plane of the tubular 30-watt source and in the direction of maximum intensity as indicated in *A* and *C* of Fig. 73. (After L. J. Buttolph.[64])

The number of germicidal sources of a given wattage used in appropriate equipment for irradiating the air above the 7-foot level varies as the area of the room for a given height of ceiling. The effectiveness of a germicidal fixture increases with the average length of the rays and, therefore, with the distance across the room. The number of fixtures

containing a germicidal source of a given wattage varies with the average dimension of the room. The inherent effectiveness of the fixture itself varies with its contour and is dependent upon the direction of the maximum intensity of germicidal energy.

Some fixtures emit their maximal intensities of energy through much more air than others. A fixture whose maximal intensities are at 35 to 40 degrees above the horizontal may be considered to be quite effective up to a distance of 10 feet. A fixture whose maximal intensities are in directions 15 to 20 degrees above the horizontal are similarly effective up to a distance of 20 feet. Therefore, these two types of fixtures may be considered to be effective over horizontal areas of 150 and 300 sq. ft., respectively, for the same germicidal source.

In general germicidal fixtures should not be located in corners of rooms. The germicidal rays should be given all the opportunity possible to cover distance before suffering almost complete absorption by surfaces, as is desirable in occupied rooms.

The number of 15-watt or 30-watt germicidal sources for a 99-percent kill of air-borne B. coli (or equivalent) in a room of certain dimensions is found in Table XXVI. Buttolph [64] developed these simplified specifications from data presented in this chapter and from other sources. It will be noted that in rooms of low ceilings only a 90- or 70-percent kill is achieved by the number of sources specified. This can readily be increased to more than a 99-percent kill by doubling the wattage of germicidal energy indicated in the table. It is assumed that the germicidal sources are used in fixtures of appropriate design in each case.

A blank place in Table XXVI means that the number of sources indicated in the same column above the particular blank space is more than sufficient. For example, for a

room 10 to 13 feet long with a ceiling height of 14 to 25 feet, one 15-watt germicidal source is sufficient for widths from 10 to 39 feet.

Table XXVI is based upon killing B. coli in the upper irradiated space. Many organisms are more resistant than B. coli. Besides, for these installations to be effective, there must be an adequate circulation of air between the irradiated space and that of the occupants. It is likely that Table XXVI represents minimum requirements in many occupied interiors. For killing most fungi, yeasts, etc., the number of germicidal lamps indicated in Table XXVI should be increased considerably.

TABLE XXVI

Simplified Specifications of 15-Watt and 30-Watt Germicidal Sources for Rooms of Various Ceiling-Heights and Floor Dimensions for the Indicated Percentages of Air-borne B. Coli Killed

	Room length, feet													
	10 to 13		*14 to 18*		*19 to 24*		*25 to 31*		*32 to 39*		*40 to 48*		*49 to 58*	
Germicidal source	*15 w.*	*30 w*	*15 w.*	*30 w.*	*15 w.*	*30 w.*	*15 w.*	*30 w.*	*15 w.*	*30 w.*	*15 w.*	*30 w.*	*15 w.*	*30 w.*
Room Width in Feet	*Rooms with 14-foot to 25-foot ceilings for 99-percent kill*													
10 to 13	1	..	1	..	2	1	2	1	3	1	4	2	5	2
14 to 18	..	..	2	1	3	1	2	1	4	2	5	2	6	3
19 to 24	..	..	..	..	3	1	3	1	5	2	6	3	7	3
25 to 31	..	..	..	..	..	..	4	2	6	3	7	3	8	4
32 to 39	..	..	..	..	..	..	..	..	7	3	8	4	9	4
	Rooms with 11-foot to 13-foot ceilings for 99-percent kill													
10 to 13	2	1	2	1	2	1	3	1	5	2	6	3	8	4
14 to 18	..	..	3	1	3	1	4	2	6	3	7	3	9	4
19 to 24	..	..	..	..	4	2	5	2	7	3	9	4	11	5
25 to 31	..	..	..	..	..	..	6	3	9	4	10	5	12	6
32 to 39	..	..	..	..	..	..	..	..	10	5	12	6	14	7
	Rooms with 9-foot to 10-foot ceilings for 90-percent kill or with 8-foot ceilings for 70-percent kill													
10 to 13	1	..	1	..	2	1	2	1	3	1	4	2	5	2
14 to 18	..	..	2	1	2	1	2	1	4	2	5	2	6	3
19 to 24	..	..	..	..	3	1	3	1	5	2	6	3	7	3
25 to 31	..	..	..	..	..	..	4	2	6	3	7	3	8	4
32 to 39	..	..	..	..	..	..	..	..	7	3	8	4	9	4
	Rooms with 9-foot to 10-foot ceilings for 99-percent kill or with 8-foot ceilings for 90-percent kill. Occupants exposed not more than 8 hours daily													
10 to 13	2	1	2	1	3	1	4	2	6	3	8	4	10	5
14 to 18	..	..	3	1	4	2	5	2	8	4	10	5	12	6
19 to 24	..	..	..	..	5	2	6	3	10	5	12	6	14	7
25 to 31	..	..	..	..	..	..	7	3	12	6	14	7	16	8
32 to 39	..	..	..	..	..	..	..	..	14	7	16	8	18	9

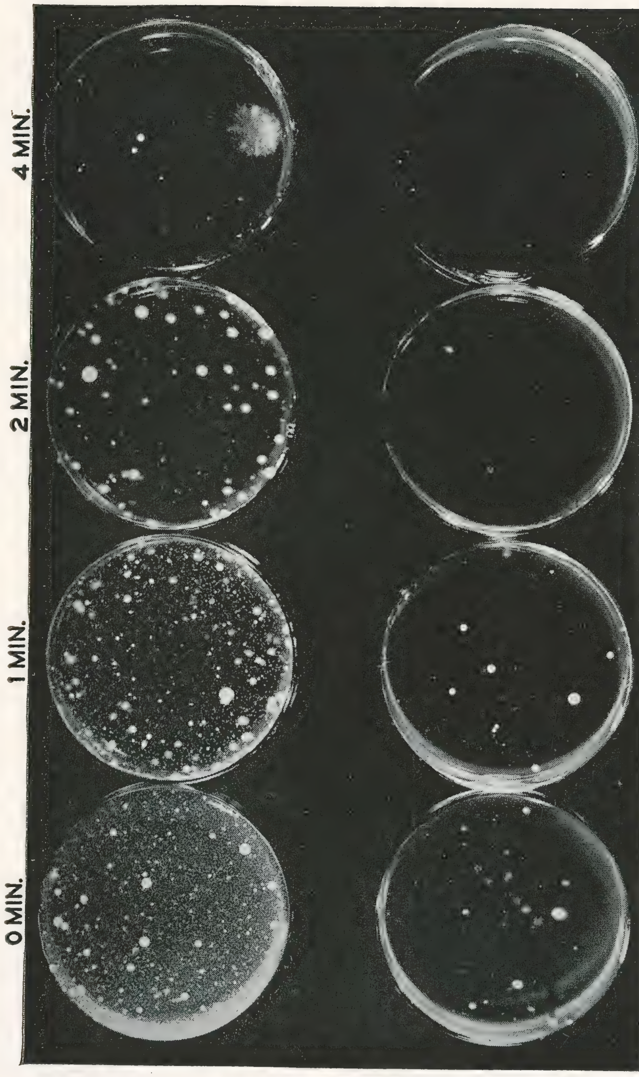


PLATE IX. Nutrient Agar in petri dishes was infected with a mixture of water from fish pools and irradiated with an intensity of germicidal flux of 150 microwatts per sq. cm. for the number of minutes indicated in each case. Most of the organisms were killed in 2 minutes or by an exposure of 300 microwatt-minutes per sq. cm.

Disinfecting Water

THE PRIMARY requisite of water for drinking purposes is that it be free of pathogenic organisms. Cholera, typhoid and paratyphoid, and bacillary and amoebic dysentery are due to water-borne organisms. At the present time poliomyelitis is suspected of being water-borne. At any rate, it is generally recognized that micro-organisms must be killed or removed from water as a preventive measure. Filtration and chlorination are practiced on large scales in municipal water supply. These are effective and relatively inexpensive processes in cities which daily supply 100 to 200 gallons of water per inhabitant who drinks only a quart of it. Disinfection by ultraviolet energy at the present time cannot possibly compete with large-scale chlorination. However, there are many small communities and individuals that need safe drinking water. Also there are countless other needs for disinfected or sterilized water.

With the advent of the quartz mercury-arc several decades ago, interest developed in its use for disinfecting water for drinking purposes and industrial processes. Many were installed for treating the water of swimming pools. However, the quartz mercury-arc had certain physical disadvantages. It is essentially a relatively high-wattage source and the heating effect often renders it difficult or impracticable to use. The 360-watt quartz mercury-arc, as shown in Table XVII, emits considerable germicidal energy. At a distance of one meter it is about 20 times as effective in killing water-borne B. coli as the noon sunlight in midsummer. (Figs. 36 and 37.) Notwithstanding this successful

challenging of the sun, the quartz mercury-arc did not come into extensive use.

A new challenger has arrived in the form of a low-pressure mercury-arc. It is inherently a low-wattage source and of much higher germicidal efficiency than the relatively high-pressure quartz mercury-arc. The output of germicidal flux of the present standard 30-watt germicidal source is about 9 times as great *per watt* as the quartz mercury-arc. In other words, the 30-watt germicidal source is about 80 percent as effective in killing bacteria as the older 360-watt quartz mercury-arc. This enormous increase in germicidal efficiency of artificial sources has inspired a re-examination of the questions and problems of disinfection of water and other liquids by means of ultraviolet energy. Extensive investigations have already yielded basic data and principles on which technology is constructed. It is rather surprising that only a relatively scanty basic knowledge had been developed during the decades in which the high-pressure quartz mercury-arc was being promoted for water disinfection.

The advantages of disinfecting drinking water by means of ultraviolet energy are generally self-evident. The water itself undergoes no significant change. Materials in solution which give drinking water its pleasing qualities are retained. Nothing is added to the water to impair its taste or odor. The degree of disinfection can be as nearly complete as desired. However, practical applications extend beyond drinking water into many fields. The pathogenic organisms are generally killed with ease as is evidenced by experiments with water-borne B. coli. In many cases only the disease-producing organisms are of interest, but when all the organisms must be killed, much higher resistivities are involved.

In Plate IX are shown some results obtained by exposing a mixture of waters from fish pools. Practically all the organisms were killed in 6 minutes by an intensity of germicidal flux of 150 microwatts per sq. cm. As seen in Fig. 78 a 99.99-percent kill of water-borne B. coli would be achieved in 2 minutes by the same intensity. However, some organisms are even still more difficult to kill.

In Plate VI are shown some results with fungi. Shallow layers were exposed in petri dishes to 200 microwatts per sq. cm. for different periods of time from 0 to 20 minutes. Apparently many organisms were killed in the first 3 minutes, but it is obvious that some resisted an exposure of 4000 microwatt-minutes per sq. cm. This is more than 10 times the exposure which effects an almost complete kill of water-borne B. coli. In fact, these resistant organisms and many others can withstand much greater exposures. Some may not succumb to any practicable exposure to germicidal energy.

The foregoing glimpses are presented at the outset of the present discussion. They emphasize certain limitations of water disinfection. However, there are many possibilities involving the killing of pathogenic and many other organisms. Here we shall present the known facts and develop the principles involved. Practical application must meet the specific requirements in each case. That distilled water, artificially infected by adding a solution of B. coli in a suitable nutrient, can be readily disinfected is illustrated in Fig. 82. Such results were obtained by exposing the infected water for about one minute to an intensity of 400 microwatts per sq. cm. The disinfection is so nearly complete that one may say the water was sterilized. Apparently B. coli in water are 5 to 10 times as resistant as in air of various humidities.

ABSORPTION AND TRANSMISSION OF WATER

In dealing with disinfection of air, the matter of absorption of the air can be ignored. For distances generally encountered indoors, the transmission-factor of the air may be considered to be practically unity or 100 percent. In other words, there is no significant absorption of energy of $\lambda 2537$ by ordinary depths of air. This is not true of water and other liquids. Water from various sources has significant absorption-coefficients which vary over a considerable range. Since the germicidal energy must reach the water-borne bacteria in sufficient intensity for a sufficient period of time, the relationship between transmission-factor and depth of a given water must be established.

In Fig. 76 are shown such relationships for 8 clear waters taken from various sources as indicated. For a homogeneous medium, the transmission-factor t of radiant energy of wavelength λ varies exponentially with the depth d. In the case of germicidal energy from the new low-pressure mercury-arcs, the energy may be considered to be concentrated at $\lambda 2537$. Therefore,

$$\frac{t}{1-r} = e^{-ad} \quad \text{or} \quad t = 0.98e^{-ad}$$

where r is the fraction (approximately 0.02) reflected at the surface of the liquid and a is the absorption-coefficient of the medium. The plotted values become 98 percent for zero depth as illustrated in Fig. 76. If the measurements of transmission-factor are made in such a manner that the effect of reflection by the surface is not included, the exponential law for clear non-turbid homogeneous water is

$$t = e^{-ad}$$

For various specimens of water it was found that the straight-line relationship illustrated in Fig. 76 holds to at

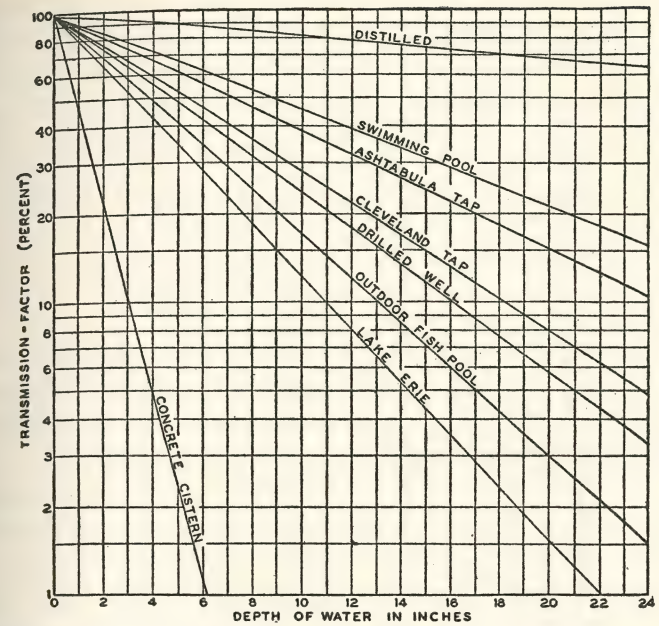


FIG. 76. Showing transmission-factor for the energy ($\lambda 2537$) from a standard germicidal source for various depths of eight different clear waters.

TABLE XXVII

The Absorption Coefficients a for Energy of $\lambda 2537$ per Centimeter and per Foot Thickness of Various Waters, and the Percentages of This Energy Transmitted to Various Depths in Inches

Source of Water	*Absorption Coefficient* Per Cm.	Per Ft.	*Percent Transmitted to Various Depths* 3 In.	6 In.	12 In.	24 In.
Distilled	0.008	0.24	92	88	78	61
Swimming pool	0.031	0.94	78	62	39	15
Ashtabula tap	0.037	1.14	74	56	32	10
Cleveland tap	0.050	1.52	67	46	22	4.7
Drilled well	0.056	1.72	64	42	18	3.1
Fish pool	0.070	2.14	58	34	12	1.3
Lake Erie	0.083	2.53	52	28	8	0.6
Concrete cistern	0.297	9.05	10	1	..	..

least a depth of 24 inches or to a transmission-factor of one percent. In order to complete the physical analysis for these 8 different waters, the absorption-coefficients and percentages transmitted by various depths are presented in Table XXVII.

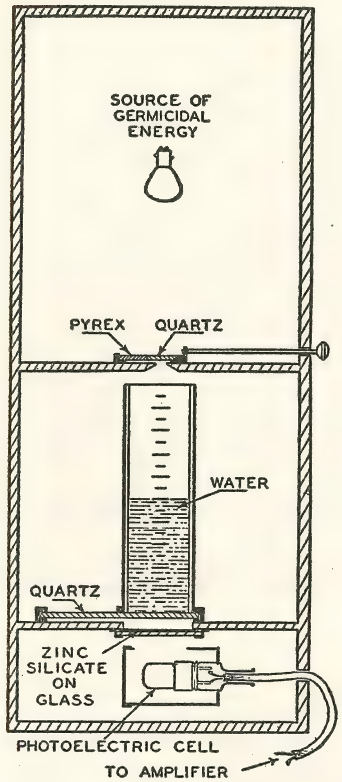


FIG. 77. A device for measuring the transmission and absorption-coefficients of clear water quickly and accurately.

MEASUREMENT OF TRANSMISSION

Apparatus designed and used for rapid measurements [67] of the transmission of water is illustrated in Fig. 77. The source of germicidal energy is of special laboratory design with ultraviolet-transmitting glass bulb and it emits most of its ultraviolet energy in the neighborhood of λ2537. The energy emitted in the spectral region λ2950–λ3150, where there are three prominent mercury lines, is only about 2 percent of that in the λ2537 region. The germicidal energy passes through clear quartz and a limiting diaphragm and is then transmitted by the water in a vertical water-cell with a bottom of clear quartz, and is finally incident upon a zinc silicate phosphor on glass. The λ2537 energy produces a strong greenish fluorescence in this phosphor and the measurement of relative brightness of the phosphor is

made by means of an RCA No. 929 phototube and an amplifier.[65] The high concentration of energy in the λ2537 region and high response of the phosphor in that region combine to make the fluorescence due to that spectral line over 99 percent of the total fluorescence. By using a differential shutter of quartz and pyrex, respectively, at the diaphragm, the response of the phototube to near-ultraviolet and visible energy, transmitted by the glass plate on which the phosphor is coated, is automatically compensated.

The water-cell can be moved along a track so that it is removed from the beam and the extended quartz base substituted for it. Thus a "zero-thickness" reading can be taken at any time without emptying the water-cell. It has been found experimentally that the water-cell with a thin film of water has approximately the same transmission as the quartz plate extension, thus making it unnecessary to correct the observations for reflection at the surface of the water. The diaphragm limits the beam well within the area of the bottom of the cell so that no radiant energy from the source strikes the cell walls directly. Thus all energy transmitted by the sample of water impinges upon the phosphor and there is no effective change in the length of optical path with different thicknesses of water.

EFFECT OF MINUTE IMPURITIES

Some investigations were made to ascertain the constituents of clear water responsible for decreasing its transmission of germicidal energy of λ2537. Typical constituents of common drinking waters were added to double distilled water in amounts varying from 1 to 100 parts per million by weight. No great decrease in transmission-factor was found for calcium chloride, calcium carbonate, calcium sulfate, magnesium chloride, magnesium carbonate, mag-

nesium sulfate, sodium chloride, sodium carbonate, sodium sulfate and aluminum oxide. Even a mixture of 200 parts each of sodium chloride, sodium sulfate and sodium carbonate in a million parts of double distilled water decreased the transmission-factor of a 5-inch depth only from 93 to 88 percent. However, one part of iron oxide caused a reduction from 93 to 35 percent. Adding one part of iron, by way of ferric chloride solution, to one million parts of double distilled water reduced the transmission-factor of a 5-inch depth from 93 to 7 percent. The addition of one part of iron, by way of ferric sulfate solution containing ferric oxide precipitate, to a million parts of the distilled water caused a reduction from 93 to 27 percent.

From the foregoing it is seen that of the constituents tested, iron is an outstanding cause of absorption of energy of $\lambda 2537$ by ordinary clear waters. This is not surprising, for iron performs this same function in glass. If a glass is to transmit energy in the region of $\lambda 2537$, it must be practically free of iron. In public water supplies, iron is commonly present in quantities from 0.02 to 7 parts per million. The average from 54 sources was found to be 0.6 part per million.

The decrease in the transmission-factor of water due to iron was demonstrated by putting a steel tack in distilled water. After 72 hours, the transmission-factor of a 5-inch depth was reduced from 93 to 61 percent. After this water was passed through a coarse fritted glass filter, the transmission-factor increased to 79 percent.

A steel tack was placed in a pint of Cleveland water from a cold-water tap. After 72 hours, the transmission-factor of a 5-inch depth decreased from 53 to 19 percent. After passing this water through a coarse fritted-glass filter, the transmission-factor increased from 19 to 40 percent.

The foregoing glimpses reveal the great influence of

minute quantities of iron in decreasing the transmission-coefficient of clear water. A few more examples illustrate the extreme sensitivity of absorption- and transmission-coefficients to minute quantities of foreign materials in solution or suspension. The use of fine fritted-glass filters showed that some of the waters from various sources contained some material in suspension even though it was not visible as such. In the following cases the transmission-factors apply *to a 5-inch depth of water.*

The transmission-factors of water from cold-water taps in 26 large cities varied from 8 to 70 percent. Their absorption-coefficients a varied from 0.46 to 0.066 per inch or 0.18 to 0.026 per cm., respectively.

Cleveland water taken from adjacent cold-water and hot-water taps had transmission-factors of 53 and 34 percent, respectively.

Cleveland water from the same cold-water tap was placed in a glass bottle having an ordinary cork. The bottle was inverted for several days. Apparently the contamination due to the water-soaked cork reduced the transmission-factor from 53 to 34 percent. Water from the same cold-water tap was stored in a glass-stoppered bottle for 15 days without any change in transmission-factor.

Water from this same cold-water tap was treated several ways and the transmission-factors were found to be as follows: untreated, 53 percent; heated to 80° C. and cooled, 50 percent; heated to boiling point and cooled, 48 percent; boiled 10 minutes and cooled, 43 percent; untreated but passed through a coarse fritted-glass filter, no change; boiled 40 minutes and passed through same filter, 42 percent. A pyrex vessel was used in heating the water.

Reducing the temperature of the water from the cold-water tap from 25° C. to 4° C. did not affect its transmission-factor.

A 5-inch depth of double-distilled water had a transmission-factor of 95 percent. There was no change after passing through a fritted-glass filter, but after passing through two ordinary filter papers the transmission-factor decreased to 58 percent.

Several common rubber gaskets for glass jars were allowed to soak for 24 hours in a glass jar containing a pint of water from the cold-water tap. The transmission-factor of a 5-inch depth was decreased from 53 to 6 percent.

As seen later, the samples of water obtained from some cities had relatively low transmission-coefficients. One of these samples appeared to have material in suspension. By passing through a coarse fritted-glass filter, the transmission-factor for a 5-inch depth increased from 11.6 to 15 percent. Another water from a large city contained no observable suspended matter. However, after passing through a very fine fritted-glass filter, the transmission-factor of a 5-inch depth increased from 10 to 18 percent.

The results in general reveal that the major part of the absorption of radiant energy of $\lambda 2537$ by clear drinking waters from various large municipal sources is due to materials in solution rather than in suspension. They also indicate that some possible uses of the extreme sensitivity of the transmission-coefficient of water might be made in determining minute quantities of compounds. A device such as illustrated in Fig. 77 might have some applications in the quantitative measurement of materials in solution. By careful calibration in terms of chemical analyses, valuable information might be yielded in a relatively easy manner.

EFFECT OF IRRADIATION ON ABSORPTION

In the course of accurate measurements on the influence of minute impurities upon the absorption-coefficient

of water, it was found that intense irradiation of the water with energy of $\lambda 2537$ markedly altered the absorption. In some instances the absorption-coefficient of the water was eventually reduced to that of double-distilled water whose absorption-coefficient was $a = 0.0055$ per cm. A few examples should be of interest. In all cases the samples of water were from a municipal supply or other source of drinking water. The samples were irradiated in quartz cells for different periods of time, the intensity of germicidal energy being 3000 microwatts per sq. cm. The resulting exposures were relatively very great compared with those necessary to kill B. coli or even molds and yeasts.

A commercial mineral water sold for drinking purposes had an absorption-coefficient $a = 0.055$ per cm. before treatment. After irradiating for 24 hours a was reduced to 0.015 per cm.

A sample of Cleveland water from a cold-water tap reacted as follows to irradiation for different periods:

Hours	
0	$a = 0.047$ per cm.
0.5	0.037
1.5	0.027
3.5	0.021
19.0	0.0055

After 19 hours the absorption-coefficient had decreased to that of double distilled water and it remained at that value after irradiation when stored in quartz and glass vessels. Boiling some of this treated water for a period of 20 minutes increased a from 0.0055 to 0.027. Further irradiation again reduced the absorption-coefficient.

This same schedule was repeated with other samples of water from municipal supply systems with similar results.

By being able to make accurate measurements of the transmission of $\lambda 2537$, many interesting facts were un-

covered. All of these were investigated further, but a discussion of these aspects would lead too far afield. It is sufficient to bring to the attention of the reader the fact that exposure to germicidal energy can greatly alter the absorption and transmission of ordinary drinking water.

KILLING B. COLI IN WATER

Clear water was infected with B. coli 24 hours old by adding them to a suitable nutrient, such as Levine's Eosin Methylene Blue Agar and introducing a quantity of this infected nutrient into the water. The transmission-factors of various concentrations of the nutrient in the water were measured for various depths of the solution for germicidal energy of $\lambda 2537$. It was found that for the small amounts of infected nutrient which were added to the water, the transmission-factor was not significantly reduced. The effect of the natural dying-rate of the B. coli was eliminated by keeping all samples, exposed or unexposed to germicidal energy, in the same solution for the same length of time before transferring measured amounts to petri dishes for incubation for 24 hours at 37.5° C. The usual procedure of counting the colonies then yielded a record of the survival-ratio or percentage killed for each exposure, *Et*.

Practically a complete kill, as illustrated in Fig. 78, is obtained by an exposure of about 350 microwatt-minutes per sq. cm. The unit lethal exposure for B. coli in water, as determined by more than 1000 separate cultures, was found to be about 40 microwatt-minutes per sq. cm. This is 5 to 10 times as great as for air-borne B. coli in air of various common relative humidities, as illustrated in Fig. 67. This higher resistivity of water-borne B. coli is consistent with the fact that the resistivity of air-borne B. coli appears to increase with the humidity.

Apparently the relationship of the survival-ratio of water-borne B. coli and exposure appears to be adequately represented for practical purposes by the exponential equation

$$P/P_0 = e^{\frac{-Et}{Q}}$$

where E is the intensity of germicidal energy;
t is the time of exposure in minutes;
Q is the exposure (Et) which renders the exponent e equal to minus one, which is termed a unit lethal exposure or lethe as Wells has proposed.

For water-borne B. coli, Luckiesh and Holladay [66] have determined this to be 40-microwatt-minutes per sq. cm. In other words, this exposure kills 63.2 percent and obviously the survival-ratio is 36.8 percent. The exponential relationship has been questioned,[70] but the author and his colleagues found it to hold over practical ranges.

In Fig. 78 the broken line represents the average results obtained from counts of many cultures of B. coli made from samples of infected water taken before and after various exposures at various depths of water. The absorption-coefficient a of the water was 0.05 per cm. or 0.13 per inch. However, this was important only in the actual work as it affected the intensity of germicidal energy at various depths of the water. It is not involved in Fig. 78 in which exposures *Et* are plotted. The straight unbroken line represents a true exponential relationship between exposure and percent killed or survival-ratio. Many factors are involved in these techniques and the counting of the colonies is inherently an approximation. However, the exponential law appears to represent the relationship adequately for practical purposes.

In Fig. 79 is illustrated the vertical section of an aluminum tank and a double-parabolic reflector used for the basic investigations on the disinfection of water. It will

be noted that with the tubular germicidal source in the foci of the two parabolas, the space below is subjected to a cross-fire of radiant energy. The reflector was closed at the ends and long enough to accommodate a 36-inch 30-watt

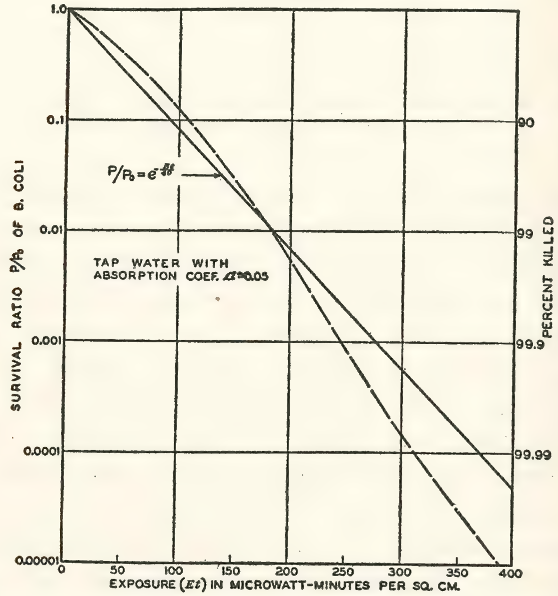


FIG. 78. Showing the relationship between survival-ratio of B. coli and germicidal exposure. The broken line represents the results of many determinations. The true exponential relationship shown by the solid line probably holds over practical ranges. (See Figs. 36 and 37.)

germicidal source. It provided a cover for the tank which held the water. For convenience, tanks of several depths were used. As will be emphasized later, tanks of this type might well be used in practice. They can be used in series or parallel or both, depending on the capacity needed.

In Fig. 79 the intensity of germicidal energy is indicated for various levels with and without a depth of 12 inches of water. In this case, Cleveland tap-water was used and its absorption-coefficient *a* was 0.05 per cm. or 0.13

per inch. As might be expected, the intensity decreases rapidly with depth of water. When the tank contained 12 inches of water, the intensity *E* of germicidal energy at the 12-inch level was 610 microwatts per sq. cm. At the same level when there was no water in the tank, the intensity at the 12-inch level was 700 microwatts per sq. cm. The

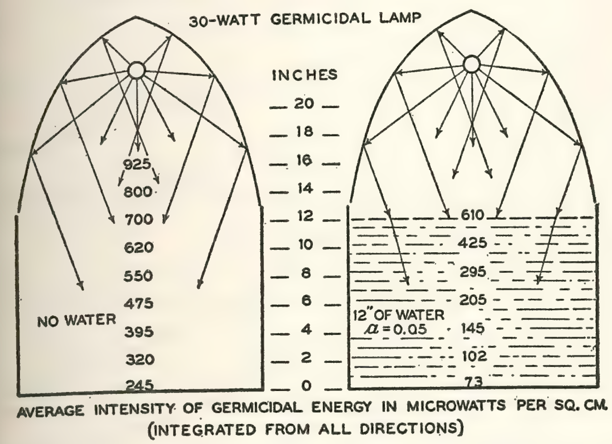


FIG. 79. Showing the decrease in intensity of germicidal energy with distance below a 30-watt source located in the foci of a double-parabolic reflector above an aluminum tank. (See Fig. 87.)

reason is that the water by its absorption reduces the amount of interreflected energy. Incidentally, with the best equipment these intensities of germicidal energy can be increased somewhat.

The energy at a given point was measured from 6 different directions. One may imagine a minute cube at each point and the intensity of germicidal energy measured at each of its facets. These are then added in order to arrive at the total germicidal energy impinging on a bacterium at that point. The values in Fig. 79 are averages of measurements made in the foregoing manner at representative points in each horizontal plane indicated.

The effect of the absorption-coefficient a of water on the intensity of germicidal energy at various depths d is illustrated in Fig. 80 for 7 specimens of clear water. Several of these specimens are the same as illustrated in Fig. 76 and Table XXVII. They represent the complete range of ab-

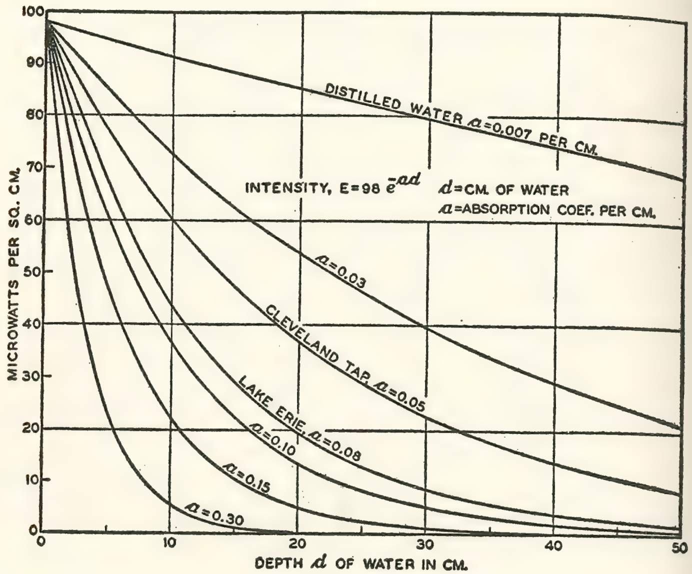


FIG. 80. The intensity of germicidal energy decreases as the depth of water increases. Data are presented for seven clear waters of different absorption-coefficients.

sorption-coefficients found in investigating many different waters. In fact, the absorption-coefficient of the water from a concrete cistern was much greater than the greatest exhibited by any municipal water examined.

The data obtained by using a standard 30-watt germicidal source in an aluminum reflector over an aluminum tank, as illustrated in Fig. 79, made it possible to determine the rate of disinfection of Cleveland tap-water (a = 0.05) containing B. coli to various survival-ratios or percentages

killed as illustrated in Fig. 81. The output of germicidal flux was that of the currently standard 30-watt source but the reflector was not as efficient as it could have been. However, the actual intensities of germicidal flux at vari-

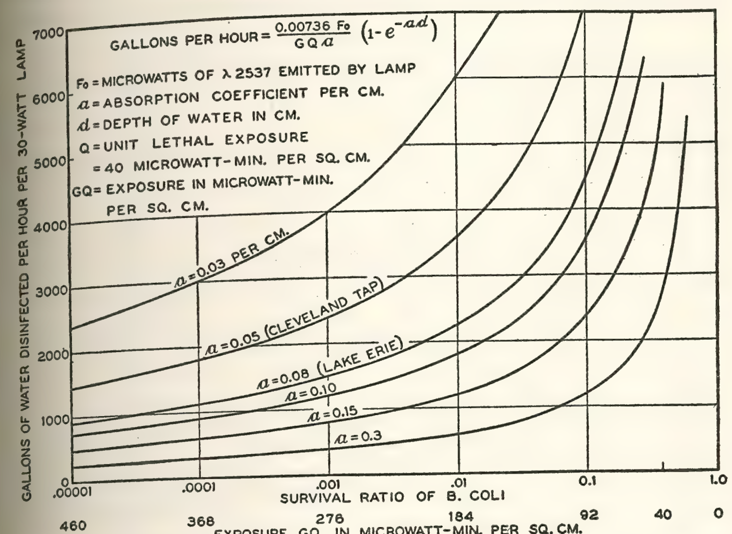


FIG. 81. Rates of disinfection per 30-watt germicidal source of various waters, infected with B. coli, for different exposures.

ous levels below the source are presented in order not to limit the data to one actual source with a specific output. The depth of the water was extended downward sufficiently so that it absorbed 90 percent of the incident germicidal flux. As seen in Fig. 76, this depth is about 18 inches for the Cleveland tap-water. The data in Fig. 81 indicate that one standard 30-watt germicidal source, used as described, can kill 99.9 percent of the B. coli—a survival-ratio of 0.001 —in more than 2000 gallons per hour of Cleveland tap-water or any clear water with a = 0.05.

From these basic data it was possible to compute the rates of disinfection for the other waters with different

absorption-coefficients. For a 99.9-percent kill the rates of disinfection appear to vary from 400 to 4000 gallons per hour. Cleveland tap-water happened to represent an approximate average of this wide range of waters. In Fig. 81 the exposure *Et* is expressed in the equation as *GQ* where

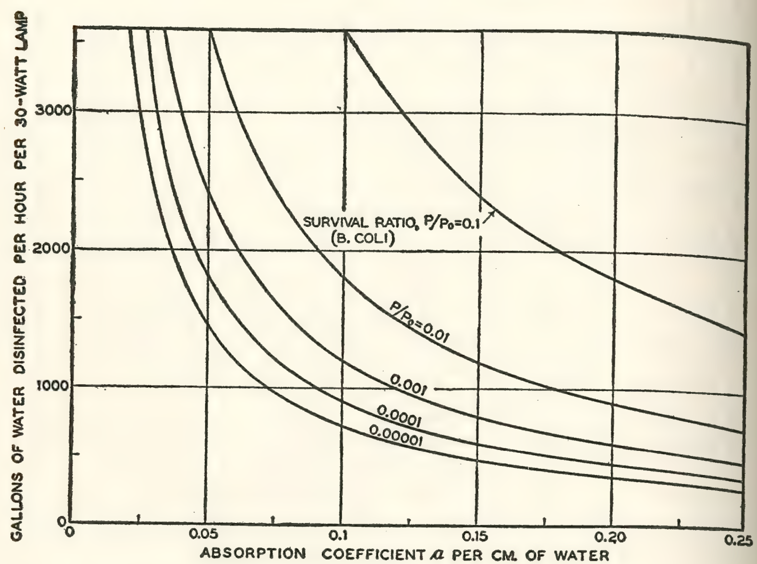


FIG. 82. The rate of disinfection of clear water depends upon the absorption-coefficient of the water.

Q is the unit lethal exposure. In the case of water-borne B. coli, *Q* was standardized at 40 microwatt-minutes per sq. cm. The number of these units in any given exposure is *G*. These symbols were used in the basic analysis to avoid confusion.

It is emphasized that the results presented in Fig. 81 apply only to clear waters with absorption-coefficients as indicated, to the particular type of installation illustrated in Fig. 79, to water-borne B. coli or organisms of similar resistivity, and to depths of water in each case which

absorb 90 percent of the germicidal flux incident on the surface of the water. The depths which absorb 90 percent of the incident energy as seen in Fig. 76 varied from 4 inches for the cistern water to 18 inches for Cleveland tap-water, to 24 inches for the Ashtabula tap-water to many many feet for the distilled water.

In Fig. 82 the same data as presented in Fig. 81 are plotted to show the relationship between rate of disinfection, in gallons per hour, per 30-watt germicidal source and the absorption-coefficient *a* per cm. of water. These data apply only to water-borne B. coli or the equivalent and include no factor of safety. They also apply only to the current standard 30-watt source emitting initially 11,000 milliwatts of germicidal flux and used as illustrated in Fig. 79 and described in the preceding paragraphs. These results are presented only as a guide. Doubtless an appreciable factor of safety must be included to cover all or most pathogenic organisms. Certainly a large one is necessary for many other organisms. In other words, the gallons per hour disinfected to any given degree will generally be less than those indicated for water-borne B. coli. In fact, as yet it is a question how far it is practicable to kill other organisms than the pathogens. Some of these are illustrated in Plates VI, VIII and IX.

Doubtless the reader has noted, and possibly has been annoyed by, the use of two systems of units. Such use is inevitable, but the author has tried to confine the use of the metric system of units to basic scientific data. This has many advantages and actually it should not be confusing. Naturally, one is forced to use the cumbersome irregular system in common use in discussions involving practical applications. Fortunately, the two units of exposure, microwatt-minutes per sq. cm. and milliwatt-minutes per sq. ft.,

are approximately equal, and for practical purposes can be used interchangeably.

If the intensity of germicidal flux, or energy of λ2537, at the surface of a clear water with an absorption-coefficient *a* is 1000 milliwatts per sq. ft., the time in minutes necessary to effect practically a complete killing of B. coli is found in Table XXVIII for various depths of the water. As already shown, algae, fungi and protozoa are at least 10 times more resistant than B. coli. Therefore, the exposure would have to be increased at least 10 times if such organisms are to be killed.

TABLE XXVIII

Time in Minutes Required for an Almost Complete Kill of B. Coli at Different Depths of Waters of Various Absorption-Coefficients *a* per Inch If 1000 Milliwatts of Energy of λ2537 Is Incident on the Surface

Absorption-Coefficient a *per Inch*	*Depth in Inches of Water* 0.1	0.2	0.5	1.0	2.0	5.0	10	20	50	100
	Minutes for Almost Complete Killing of B. Coli									
0.01	0.50	0.50	0.50	0.50	0.50	0.50	0.55	0.59	0.66	0.81
0.02	0.50	0.50	0.50	0.50	0.50	0.55	0.59	0.64	0.81	1.30
0.05	0.50	0.50	0.50	0.50	0.55	0.59	0.66	1.05	1.40	2.00
0.10	0.50	0.50	0.50	0.55	0.59	0.65	1.05	1.30	2.00	
0.20	0.50	0.50	0.55	0.59	0.64	1.05	1.30	2.00		
0.50	0.50	0.55	0.59	0.66	1.05	1.40	2.00			
1.0	0.55	0.59	0.66	0.81	1.30	2.00				
2.0	0.59	0.65	0.81	1.30	2.00					
5.0	0.65	0.81	1.40	2.00						
10	0.81	1.30	2.00							
20	1.30	2.00								
50	2.00									
100	6.00									

ALGAE, FUNGI AND PROTOZOA

Among the lower organisms which frequent water supplies are certain classes of algae, fungi and protozoa. The practicability of killing these with germicidal energy must be determined according to the needs and economics

of a given case. Energy of λ2537 is lethal to these organisms as has been shown by Meier [71] and others. Here some glimpses of unpublished work by a colleague, L. L. Holladay, are presented for the purpose of viewing the order of magnitude of the exposures involved.

Algae are green plants belonging to the lowest division of the vegetable kingdom. They contain chlorophyl and, therefore, utilize solar energy in the process of photosynthesis. There are six commonly recognized classes of algae, each of which contains a great variety of forms. In water-supply, there are three important classes; namely, the diatoms, the green algae and the blue algae.

Various specimens of algae were obtained from common sources and exposed in glass dishes with not more than a 0.3-inch depth of water. A 30-watt germicidal source supplied 200 to 400 microwatts per sq. cm. of energy of λ2537 on the surface of the water. The specimens were incubated in various waters that had been boiled. In three days to a week after the algae had been irradiated, they became more or less bleached or colorless and they disintegrated, forming a deposit on the bottom of the container. By observation under the microscope, it was possible to determine roughly the minimum exposure that was lethal. The entire technique appears simple, but many factors are involved. Therefore, the results are at best only approximations.

For diatoms, 4 different green algae and 4 different blue-green algae, the minimum lethal exposures varied from 18,000 to 30,000 microwatt-minutes per sq. cm. These are of the order of 50 times the exposure necessary to effect almost a complete killing of water-borne B. coli. No great accuracy is claimed for these determinations, but they have some value in the present early stage of applications of germicidal energy.

Fungi also include many of the lowest forms of plant life, but unlike algae, they do not contain chlorophyl. Therefore, fungi cannot synthesize their food from carbon dioxide, solar energy, water and mineral matter. They must depend for their food upon organic matter produced by animals and other plants. Thus fungi are either parasitic or saprophytic, if they live on their remains. They are divided according to their structure and mode of reproduction into three classes containing more than two dozen orders and into many thousands of species. Some are pathogenic to man.

Micro-organisms known as yeasts are unicellular forms of fungi characterized by their manner of multiplication or cell-division known as budding. The cells are spherical or egg-shaped, possessing a well-defined cell-wall, and do not develop a filamentous growth or mycelium as molds do.

Fungi obtained from various sources were exposed to intensities of energy of $\lambda 2537$ varying from 50 to 400 microwatts per sq. cm. In some cases the infected water was exposed in shallow glass dishes. Then a measured amount of this water was mixed with a culture medium and incubated. In other cases the fungi were sprayed on the surface of a culture medium. In still other cases spores were irradiated in dry dishes for various periods of time and then sprinkled on the surface of a culture medium.

The results of many tests with fungi from pools, decaying leaves, manure and soil indicate that about 2000 microwatt-minutes per sq. cm. generally resulted in a practically complete kill. Spores appeared to be 10 times as resistant. Rhizopus spores were not entirely killed by an exposure of 16,000 microwatt-minutes per sq. cm.

The protozoa, comprising the lowest group of the animal kingdom, are generally single-celled organisms.

They generally multiply by fission of the body into two organisms. For the most part they live in sea and fresh water. All higher forms of animal life harbor these parasitic protozoans and some are pathogenic to man and his domesticated animals. Certainly these are undesirable in drinking water.

Paramecia are protozoa. They may or may not be representative as to resistivity to energy of $\lambda 2537$. A series of exposures indicated that 3200 to 5000 microwatt-minutes per sq. cm. were necessary to effect an almost complete kill of these organisms. According to these tests they are about 10 times as resistant as water-borne B. coli.

The foregoing are merely glimpses of the order of magnitude of the resistivities of various micro-organisms. The quantitative values are to be considered only rough approximations.

WATERS FROM VARIOUS CITIES

In order to ascertain the various limitations of different waters, particularly the range of their absorption-coefficients, waters from many sources were obtained. These were drawn from cold-water taps into sterilized glass-stoppered bottles. In Table XXIX the specimens represent the complete range of absorption-factors found among many samples examined. As seen in the foregoing sections, the absorption-coefficient is grossly affected by minute quantities of materials in solution. Therefore, the values given in Table XXIX as determined by Luckiesh, Taylor and Kerr [67] are by no means to be considered invariable. In fact, waters obtained from other outlets of the municipal supply in some of these cities showed a marked difference in absorption-coefficient. However, these data are of great practical interest in revealing the range and order of mag-

nitude of the absorption-coefficients of waters from large municipal supply systems.

It is particularly interesting to note the range of depth of the various waters for an absorption of 90 percent of the germicidal flux incident upon the surface of the water.

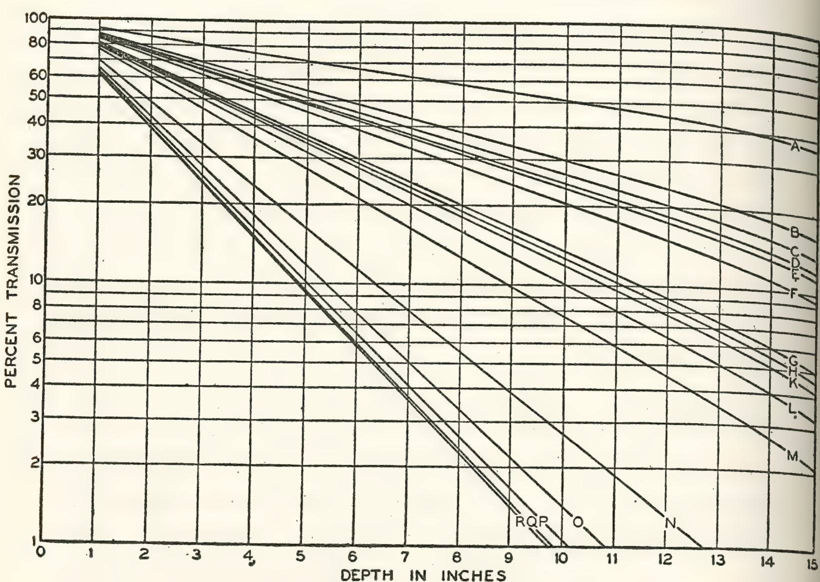


FIG. 83. The transmission-factors of various depths of clear waters from different sources.

This is an important factor, for high efficiency in the disinfection of water requires that most of the energy be absorbed in the water where it is useful. Any of the energy absorbed by the surfaces of the water-container is irrevocably lost.

In Fig. 83 the relationship between the transmission-factor, or percent transmission at λ2537, and depth of each water is plotted in accordance with the exponential law which holds for a homogeneous medium such as clear

water. By plotting on a semi-log graph the resulting straight lines are convenient in several ways. The identifications of these waters are found in Table XXIX. It is seen that the extreme range is within that represented by the eight specimens in Fig. 76. None was as absorbing as the water from a

TABLE XXIX

The Transmission of Germicidal Energy (λ2537) by Water from Various Cities. The Transmission Varies Exponentially with the Depth of Clear Water

See Fig. 83	City	Absorption Coefficient a Per Cm.	Per In.	Percent Transmitted by 3 In.	6 In.	12 In.	Inches for 90% Absorp.
A	Atlanta	0.0258	0.0656	80	66	45	34.8
B	Cleveland	0.0471	0.120	68	48	23	19.1
C	Philadelphia	0.0514	0.131	66	45	20	17.5
D	Buffalo	0.0546	0.139	65	43	19	16.5
E	Detroit	0.0562	0.143	64	42	18	16.0
F	Chicago	0.0611	0.155	62	39	15	14.7
G	Pittsburgh	0.0782	0.199	54	30	9	11.5
G	LaGrange, Ill.	0.0782	0.199	54	30	9	11.5
H	New York	0.0804	0.204	53	29	8.5	11.2
H	Dallas	0.0804	0.204	53	29	8.5	11.2
K	Portland, Ore.	0.0827	0.210	52	28	7.9	10.9
L	Denver	0.0896	0.228	49	25	6.4	10.0
M	Oakland, Calif.	0.102	0.258	45	21	4.4	8.85
N	Minneapolis	0.142	0.360	33	11	1.3	6.34
O	Kansas City	0.166	0.422	28	7.8	0.62	5.41
P	Akron, Ohio	0.177	0.449	26	6.6	0.45	5.09
P	Los Angeles	0.178	0.452	25	6.5	0.43	5.04
Q	St. Louis	0.184	0.468	24	6.0	0.36	4.88
R	Boston	0.184	0.468	24	6.0	0.36	4.88

concrete cistern and none was as transmitting as the distilled water. However, some specimens approached these limits. It is particularly interesting that the same germicidal installation can treat a depth of water *A* seven times as great as of waters *P*, *Q* or *R* with equal effectiveness. This means 7 times the volume or gallons per hour can be treated per 30-watt germicidal source.

From the basic data available it is possible to compute the number of gallons of any clear water that can be dis-

infected to a given degree by each standard 30-watt source which initially emits 11,000 milliwatts of germicidal flux. The source is assumed to be used in a suitable aluminum reflector as illustrated in Figs. 79 and 87, and the water-borne organisms are assumed to have a susceptibility similar

TABLE XXX

Computed Rates of Disinfection of Water, in Gallons per Hour, for Three Percentages of B. Coli Killed for Each Standard 30-Watt Source Used as Illustrated in Fig. 79. The Specimens of Water Are Those Similarly Designated in Table XXIX

Water	*Gallons per Hour and Percentages Killed* 90	99	99.9
A	14,000	7,000	4,500
B	8,000	4,000	2,500
C	7,000	3,500	2,400
D	6,500	3,300	2,200
E	6,400	3,200	2,200
F	5,800	3,000	2,000
G	4,500	2,300	1,500
H	4,300	2,200	1,500
K	4,200	2,200	1,500
L	3,900	2,000	1,300
M	3,500	1,800	1,200
N	2,500	1,300	800
O	2,100	1,100	700
P	2,000	1,000	700
R	1,900	1,000	650

to B. coli. In order to reveal the possibilities, these computations have been made [67] for clear waters having the absorption-coefficients indicated in Table XXIX. The results are presented in Table XXX. By no means is it the intention to suggest that germicidal sources should be used for disinfecting the municipal water supply in these large cities. In these large-scale systems germicidal flux cannot possibly compete with other processes in common use. However, these specimens aid in giving an idea of achievements that might be expected in small-scale systems, isolated supplies of drinking water, in industrial processes, and

various hygienic needs and practices. However, if other organisms such as algae, fungi and protozoa are to be killed, the rates in Table XXX must be reduced to at least one-tenth. In other words, the reader might visualize the values with the last cipher eliminated.

IMMERSING THE GERMICIDAL SOURCE

In considering the disinfection of a liquid by means of ultraviolet energy, a common impulse is to immerse the source of germicidal energy in the liquid. As shown later, this method may be necessary in treating liquids having very high absorption-coefficients, but in the case of water it is inherently inefficient. Immersion also involves obvious mechanical problems. In addition to these, it should be borne in mind that if the liquid is cold, the cooling of the tube of the low-pressure mercury-arc reduces the output of germicidal energy. Inman and Thayer [68] have discussed the effect of the temperature of the glass tube on the production of mercury resonance radiation which contributes the germicidal energy. Forsythe, Adams and Barnes,[69] in presenting fundamental data on mercury-arcs, indicate that maximum germicidal efficiency of a low-pressure mercury-arc with a one-inch tube is obtained when the tube is at a temperature of about 40° C. The efficiency is reduced to about one-half when the temperature of the tube is 20° C.

Imagine a tubular germicidal source with a one-inch tube *G*, as illustrated in Fig. 84, inserted vertically in a cylinder of water having a 12-inch radius. If the water has an absorption-coefficient of 0.2 per inch, 90 percent of the germicidal energy horizontally emitted by *G* is absorbed in the 12-inch depth of water before it reaches the walls of the container. The energy which is not emitted horizontally suffers even greater absorption before reaching the wall of the container for it travels longer paths. However, for

demonstrating the points under discussion, only the energy emitted by *G* horizontally is considered and the horizontal cross-section of the cylindrical container suffices. This cross-section is divided into twelve annular rings or zones

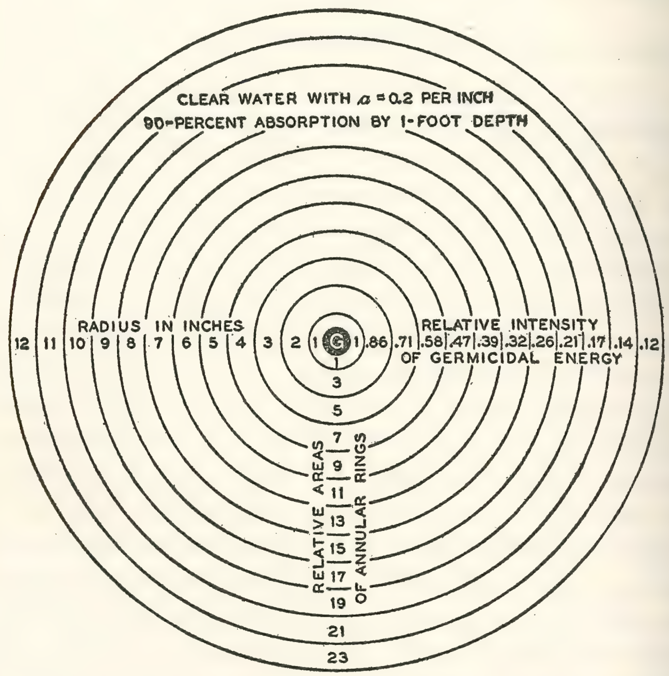


Fig. 84. Illustrating factors involved in immersing a tubular germicidal source vertically in a cylindrical tank of water.

numbered accordingly in Fig. 84. It is seen that the intensity of germicidal energy in the zone 12 is only 12 percent of that in the zone 1. Actually it is less than this for the reason that much of the energy passing through zone 1 reaches zone 12 by longer paths than that traversed by the horizontal rays. The area of zone 12 is 23 times that of zone 1. In other words, where the volume of water has

increased 2300 percent, the intensity of germicidal energy has been reduced to less than 12 percent.

There is no way of avoiding absorption of energy by the water or other liquid being irradiated. Proper circulation of the water overcomes some of the inefficiency of the foregoing static system. Baffles should be avoided if possible for they absorb germicidal energy. Where requirements demand immersion, as highly absorbing liquids may or where efficiency is not of primary interest, this method can be adopted. However, the method illustrated in Figs. 79 and 87 is inherently more efficient and avoids some of the mechanical and electrical problems of the immersion method.

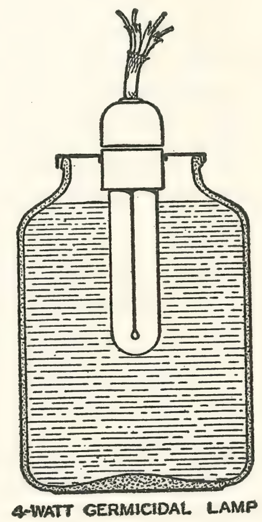


Fig. 85. This small unit is effective in disinfecting water.

In Fig. 85 is illustrated a standard 4-watt germicidal source with a base on one end. This was immersed about 6 inches in a glass jar whose inside surface was coated with aluminum by a modern process. The jar contained about one quart of clear water infected with B. coli in a small amount of suitable nutrient. In less than two minutes of exposure the water was practically completely sterilized. Rarely were B. coli found alive after 2 minutes. In one minute about 97 percent were killed.

An 8-watt germicidal source enclosed in an additional protecting tube of 974 glass was immersed in a 5-gallon glass water-bottle nearly one foot in diameter, which contained Cleveland tap-water. About 55 percent of the ger-

micidal energy reached the walls to be absorbed there. Obviously this represents an inefficient use of the germicidal energy. About 99.99 percent of the water-borne B. coli were killed in two minutes. Even this inefficient method would result in a practically complete killing of B. coli at a rate of 150 gallons per hour. If small amounts of water are to be treated, and plenty of time is available, a 4-watt or an 8-watt lamp immersed in water at ordinary room temperatures would kill all the water-borne organisms that can be killed by germicidal energy. Certainly these glimpses reveal possibilities of individual sterilizers of drinking water in isolated places as well as for other purposes.

If it is necessary to irradiate the water while flowing in the pressure system, many designs are possible. However, all require maintenance which is inherently difficult. In small air-pressure systems it might be possible to install the germicidal source in the space occupied by air under high pressure. These tubular germicidal sources will withstand a considerable pressure. However, maintenance and renewal are difficult under these circumstances.

In Fig. 86 a quartz tube is installed with stuffing-boxes at both ends. The tubular germicidal source is not under pressure and is readily removable. The cylinder containing the water flowing under pressure is of small diameter and, therefore, in most cases much of the germicidal energy will reach the walls to be largely absorbed by them. The device is inherently inefficient, but the wattage is so low that it may be practicable for relatively small volumes of water. Means might be provided to wipe manually or automatically the walls of the quartz tube that are in contact with the water. The remaining parts can readily be maintained.

Such devices might be practical where skilled maintenance is available at regular intervals. However, wherever

practicable it is best to irradiate the water outside the pressure system.

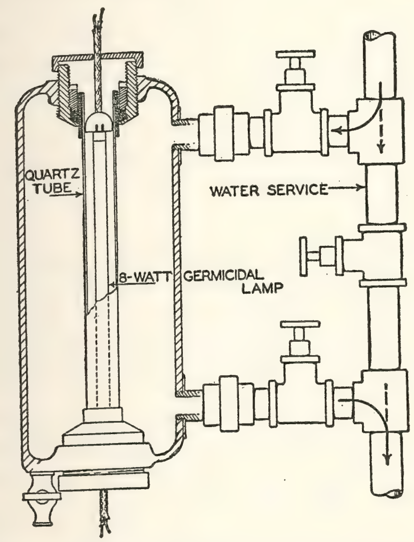


FIG. 86. Illustrating a water-disinfecting unit connected to a pressure system. Difficulties of maintenance are obvious.

IRRADIATING THE SURFACE OF WATER

As has been emphasized, disinfecting water by means of germicidal sources in suitable reflectors above the water has obvious advantages, including the less obvious greater efficiency. Vertical sections of an individual unit are illustrated in Fig. 87. The double-parabolic reflector of aluminum efficiently directs a cross-fire of germicidal energy as shown in the cross-section. The walls of the tank can be of aluminum in order to take advantage of reflection of the energy not absorbed by the water. Stainless steel has a much lower reflection-factor. The depth of the tank can be such that the vertical depth of the water absorbs most of the energy incident upon the surface of the water. The

reflector for a single unit can be hinged for convenience in cleaning the interior and replacing the sources. Naturally the bases of the lamps should be protected from the moist arc.

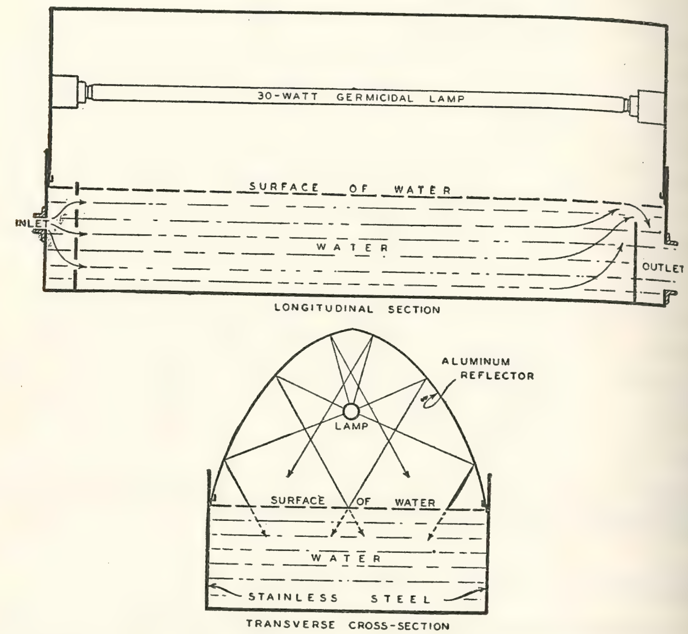


FIG. 87. A disinfecting unit for water flowing by gravity. A number of units can be connected in series or parallel depending upon requirements.

In the longitudinal section of Fig. 87, the flow of the water is indicated. Baffles for mixing the water are not indicated inasmuch as they absorb considerable germicidal energy. The water is shown rising toward the top in the vicinity of the outlet. In Fig. 79 the intensities of germicidal energy at the surface and at different levels of the water are indicated. Higher intensities than these can be obtained by such a design as illustrated in Fig. 86. Actually 1000

milliwatts per sq. ft. are attainable at the surface of the water by means of a standard 30-watt germicidal source contained in a highly efficient reflector close-coupled to the tank containing the water.

The rate of flow of water depends upon the exposure *Et* available and necessary to effect the degree of disinfection desired. If the intensity is such that 2 minutes is sufficient time, the container can be emptied and filled 30 successive times per hour. Obviously the volume of the tank multiplied 30 times results in the gallons per hour. Here the importance of the depth of the water becomes quite obvious. If the absorption-coefficient of the water is small, the depth can be large. All these factors determine the gallons of water that can be disinfected per 30-watt source. If twice the amount is needed that can be supplied by one unit similar to Fig. 87, two units can be used in parallel or by doubling the rate of water-flow the two units can be used in series. More can be added in various combinations to suit the requirements.

The results indicated in Figs. 81 and 82 were computed in the manner outlined in the preceding paragraph. They apply to the conditions specified and only to water-borne B. coli or organisms of equivalent susceptibility to germicidal energy. Doubtless large factors of safety are necessary in practice to guard against depreciation of the germicidal installation, possible and likely variations in the absorption-coefficient of the water, and probable greater resistivity of some pathogenic organisms. If various fungi and other organisms are to be killed, the rate of whatever disinfection is possible is bound to be much less than for B. coli.

If, for example, one 30-watt germicidal source will satisfactorily disinfect only 100 gallons of water per hour, 10 sources will take care of 24,000 gallons per 24-hour day. This would supply all the water used daily in a sizable

village. This is a large supply for an industrial process. If B. coli are reasonably representative of the organisms to be killed, it appears that one 30-watt source might satisfactorily disinfect 1000 gallons per hour in some cases. Therefore, 10 of these sources would take care of 240,000 gallons

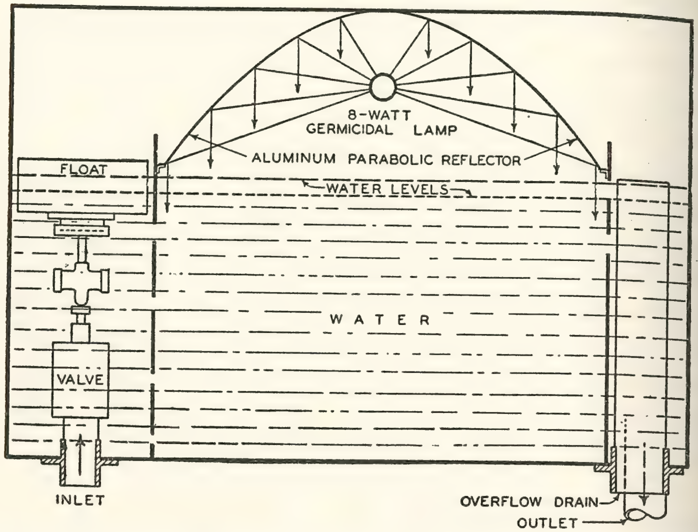


Fig. 88. A small unit containing a 4-watt or 8-watt germicidal source can be connected to the water-supply. Disinfected water can be drawn by gravity.

per day. This would supply all the water used daily in a sizable town. These are mere glimpses of the possible magnitude of applications. However, a factor of safety of at least 10 is probably necessary if algae, fungi and protozoa are to be killed.

In Fig. 88 is illustrated a small enclosed tank connected to a water supply and maintained full of water by a float-valve. A germicidal source is installed above the water in a suitable parabolic reflector with closed ends. Disinfected water may be drawn from this tank by gravity. One of

these containing a 4-watt source was installed 3 feet above a mechanical water cooler to which it was properly connected as illustrated in Fig. 89. The water flowed by

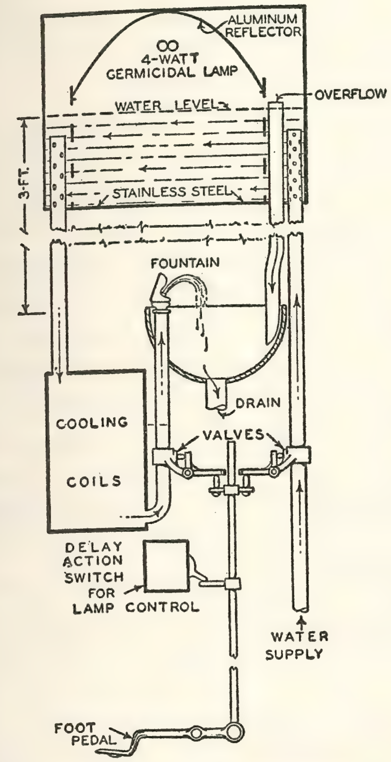


Fig. 89. An application of a germicidal unit to a water-cooler. The water reaches the fountain by gravity. A 3-foot head is satisfactory for a drinking fountain.

gravity from the upper tank to the cooling coils and the drinking fountain. The germicidal source may be operated continually or automatically for a given period every time water is drawn from the cooler. These are mere glimpses into a possible new era of water-disinfection.

Fig. 90 illustrates a completely portable battery-operated device that is practicable. The output of this small 4-watt source is of relatively low germicidal efficiency. Tests showed that most of the B. coli were killed in one minute and practically all of them in 2 or 3 minutes. (See Fig. 92.)

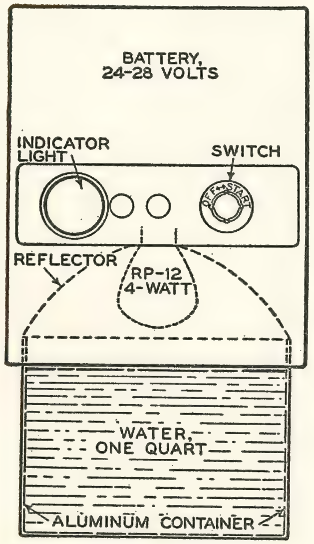


Fig. 90. A portable disinfecting unit for disinfecting small quantities of water.

In using the quartz mercury-arc for the disinfection of water, past practice was not based upon all the principles which would result in maximal efficiency. As emphasized in the present work, the first principle is that of absorbing most of the germicidal energy in the water which is being disinfected. If one wishes to irradiate water under pressure through a quartz window *Q* from a source *G* outside in a reflector *R*, Fig. 91 illustrates sound fundamental design for efficiency. It is seen by the length of the different rays shown and by the curvature of the inner surface of the irradiation chamber that maximal efficiency would be approached for a water with a given *a* by constructing such an apparatus of suitable dimensions. The shorter rays such as *A* strike the wall at grazing angles, thereby suffering less absorption. The longer rays *C* are diminished to a low intensity before they reach the wall. Such rays as *B* travel a considerable path in water and then strike the wall at a large angle of incidence.

COMMERCIAL SPRING WATERS

Many spring waters are bottled and sold. Commonly the water flows into a storage tank from which it is drawn for bottling. Very generally it is desirable to preserve the original taste of the water. This limits the use of chemicals.

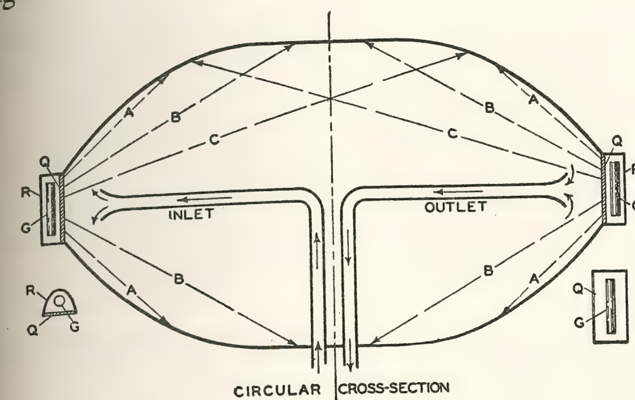


Fig. 91. An arrangement for disinfecting water under pressure from an external germicidal source. This design utilizes the energy efficiently by several expedients.

Here is an opportunity to use germicidal energy as insurance against pathogenic organisms at all times of the year. The water may be irradiated in the storage tank and also by means of units such as illustrated in Fig. 87.

Several spring waters investigated were found to have absorption-coefficients from 0.03 to 0.055 per inch. These rank among the more transmitting of the samples considered in Table XXIX. Apparently the range of *a* among spring or socalled mineral waters is about the same as that found in waters from large cities. Therefore, the lowest rate of disinfection on the basis of B. coli would generally be high compared with a flowing spring. If a spring flowed 100 gallons per hour, one 30-watt unit should provide a reasonable factor of safety against pathogenic organisms.

OCEAN WATER

One might expect ocean water with its long-time accumulation of salts to be highly absorbing of energy of λ2537. However, measurements indicate that the absorp-

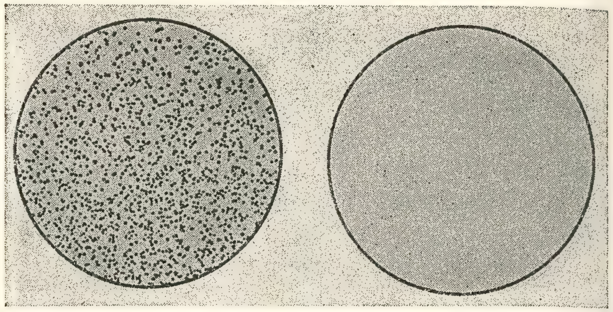


FIG. 92. Illustrating petri dishes exposed to air artificially infected with B. coli before and after the air was irradiated with a dosage of germicidal energy sufficient to effect a complete kill.

tion-coefficients of salt water are within the range found for drinking waters. For example, water taken from Long Island Sound, two miles off Orient Point, had $a = 0.09$ per cm. and 0.23 per inch. A depth of 10 inches absorbed 90 percent of the incident energy of λ2537.

Water taken from East River in New York City had an $a = 0.386$ per inch. A depth of 8 inches absorbed 90 percent of the incident energy of λ2537.

It appears that the materials such as iron compounds which are chiefly responsible for the absorption of germicidal energy do not accumulate in abnormal quantities in ocean water. They appear to be more prevalent in some river waters. Certainly they are relatively abundant in the water from the concrete cistern as seen in Fig. 76.

Any appreciable disinfection of water in the ocean and elsewhere must take place in the surface layers. Of

course, sunlight and skylight contain no energy of maximal germicidal effectiveness. As seen in Fig. 34, energy of λ3000 is less than 10 percent as effective as energy of λ2537 and energy of λ3100 is only about one percent as effective. According to Fig. 15, the intensity of erythemal flux at the earth's surface at noon in midsummer is less than 20 microwatts per sq. cm. Assuming that this energy is only 5 percent as effective in killing micro-organisms as energy of λ2537, it is seen that the germicidal effectiveness of noon sunlight is of the order of one microwatt per sq. cm. of energy of λ2537. Skylight contributes considerable energy in the region of λ3000 to λ3100 as indicated in Fig. 20. Assuming that this contribution is equivalent to that of noon sunlight, the germicidal effectiveness of energy in this spectral band is of the order of 2 microwatts per sq. cm. of energy of λ2537.

Even by taking into account the germicidal effectiveness of the other wavelengths, it is seen that solar energy is a weak disinfectant compared with modern artificial sources. However, it operates all day long on clear days even though with far less intensity during the early and late hours of daylight. Taking all this into consideration, it is not surprising, as is shown in Chapter V, that artificial sources of germicidal energy have overwhelmingly challenged the sun for mankind's artificial purposes. In this connection the reader might refer to Figs. 36 and 37. A 360-watt high-pressure mercury-arc, at a distance of 3 feet, is as effective germicidally in less than 3 minutes as noon sunlight is in an hour. This also means that a standard 30-watt germicidal source without a reflector and at a distance of 3 feet is 20 times as effective as average midsummer noon sunlight in the killing of micro-organisms. A comparison of the germicidal effectiveness of these two artificial sources is presented in Table XVIII.

Artificial Sunlight

In the strictest sense, artificial sunlight should have the same spectral distribution of energy as that of natural sunlight on a clear day. But natural sunlight varies greatly during the day, even on cloudless days, and throughout the year. Therefore, for certain purposes it may be necessary to establish a standardized sunlight by averaging the measurements of energy of various wavelengths which have been made on many days. For some purposes there are sound reasons for standardizing natural sunlight for the midday hours on clear days during midsummer. Generally the practical uses of artificial sunlight[1] will dictate the requirements as to intensity and spectral distribution of energy. There are many applications in therapy which aim to cure diseases or to rectify disorders. In such cases the intensity of the curative energy is often far greater than in natural sunlight. Other therapeutic applications aim only to prevent diseases or disorders by helping to maintain the health of healthy or near-healthy human beings. In such cases the effective energy may be relatively weak. The cure of diseases is the province of the medical profession, and there are many applications of ultraviolet energy, artificial sunlight and infrared energy in this field. On the other hand, the preservation of health or the prevention of diseases or disorders can be practiced by anyone with any suitable means employed in any approved manner. Many products and practices are continually contributing to human welfare. Ultraviolet energy can serve extensively in this respect.

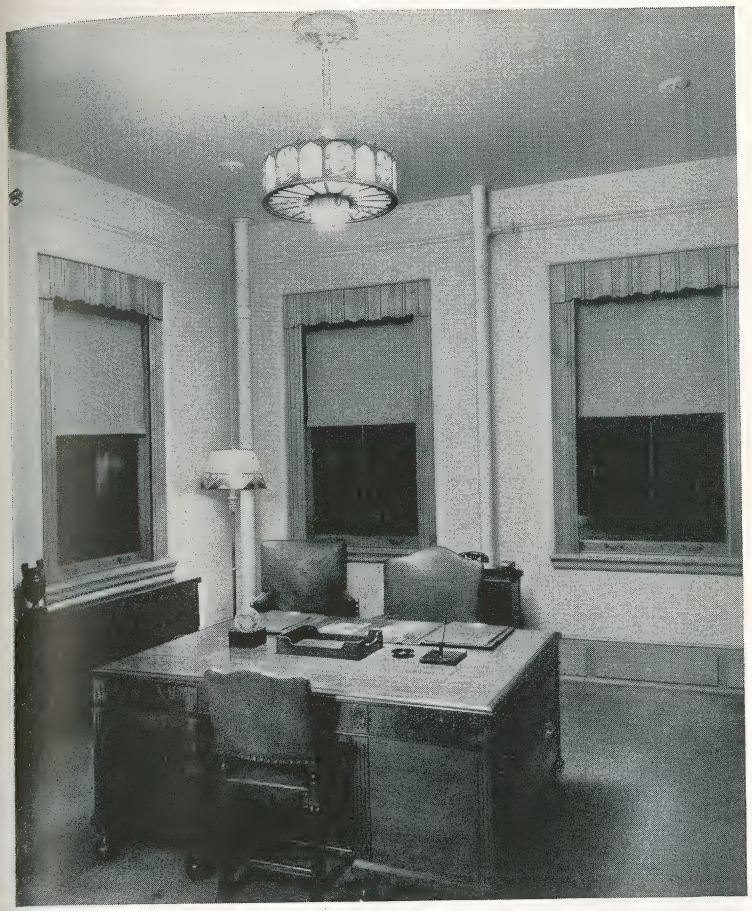


Plate X. For nearly a score of years the downward component of this fixture has supplied artificial sunlight from an S-1 sunlamp. The portable lamp is also a sunlamp suitable for reading and other seeing tasks. This dual-purpose lighting supplies biologically-beneficial ultraviolet energy while occupants are engaged in daily tasks. Now it can be supplied with fluorescent sunlamps.

Sunlamps are available for use by the medical profession and by anyone else. The term *sunlamp* is generally restricted to sources and equipment whose output of radiant energy is limited in spectral range to that of natural sunlight. They should emit no significant amount of radiant energy shorter than $\lambda 2800$. They should supply a reasonable amount of erythemal energy which is a rough indication of their therapeutic value. Other sources of radiant energy are available which supply ultraviolet energy of wavelengths beyond the short-wave limit of the solar spectrum. Such sources have long been used in a variety of therapeutic applications including the treatment of skin diseases and the killing of germs. However, for the latter purpose the new germicidal sources—low-pressure mercury-arcs—are far more efficient. There is an extensive demand and use for artificial sunlight for tanning of human skin. This is largely an esthetic or cosmetic matter, but while acquiring a tan certain health benefits are obtained. As seen in Chapter II, the most suitable energy for tanning is that of longer wavelengths than the most effective energy in the production of erythema or sunburn.

There are many uses of artificial sunlight for the testing of materials. For many years colored materials have been submitted to fading tests. The artificial sources used have generally supplied considerable ultraviolet energy, but the entire spectral range of natural sunlight generally is not closely duplicated. If it is adequately proved that a given source produces fading approximately as natural sunlight does, this specialized application is justifiable. However, such proof is difficult to obtain and, therefore, there are many real needs for an intense artificial sunlight approximating the spectral distribution of natural sunlight through the ultraviolet, visible and infrared regions. On the other hand, sunlight and skylight outdoors vary considerably in

spectral character so that it does not appear necessary to sacrifice too much in intensity and practicability by unnecessary refinement in spectral character. Long experience with various aspects of the problem leads inevitably to such a conclusion in practice.

Thus it is seen that the term *artificial sunlight* is not fixed in meaning. Strictly it means artificial radiant energy of the same intensity and spectral character as natural sunlight. In practice, it usually implies adequate ultraviolet energy from λ2900 to λ3600 as determined by erythemal and antirachitic effectiveness. By extension it could include sources which also emit ultraviolet energy of shorter wavelengths than exists in natural sunlight, provided an overall effect of such a source is comparable to that of the sun. (See Plate XVI.)

The term *artificial sunlight* also implies that natural *sunlight* produces certain effects that natural *daylight* does not. The author and his colleagues, as shown in Chapter II, have found natural skylight to be comparable to natural sunlight in the amount of short-wave ultraviolet energy supplied to the earth's surface. Therefore, natural skylight is both erythemal and antirachitic. It is also potent in other ways in which natural sunlight is effective.

The term *natural daylight* is commonly applied to light or visible energy supplied by both the sun and sky. Thus this meaning is fairly definite even though natural daylight varies considerably in color and spectral character. It may also be applied to both visible and invisible energy from the sun and sky. For example, artificial daylight for fading materials includes the ultraviolet energy as well as the visible energy reaching the earth as sunlight and as skylight, which, of course, is sunlight that is scattered *selectively* by the atmosphere.

ERYTHEMAL AND ANTIRACHITIC EFFECTIVENESS

The prevention and cure of rickets, apparently due to the direct production of Vitamin D in the fatty substances, is emphasized here as an indication of the spectral range of ultraviolet energy that is biologically effective. The technique of detecting and appraising this effect of ultraviolet energy is well established. Other beneficial physiological effects are known, but the techniques of appraisal are not well developed. Therefore, we have come to rely upon antirachitic values as a rough measure of biologic value in general. The next practical step is to use erythemal effectiveness as a rough indication of biological effectiveness. In any event, erythemal effects must be considered in exposing human beings to biologically-effective ultraviolet energy.

The relationship between erythemal and antirachitic effectiveness is not well established, but it is known that radiant energy which produces erythema of the skin also cures and prevents rickets. At least this is true for the spectral range from λ2500 to λ3200. Inasmuch as the spectral erythemal effectiveness of ultraviolet energy has been fairly well determined, and erythema is relatively easy to produce and measure, erythemal effectiveness of ultraviolet energy is conveniently used as a rough indication of antirachitic effectiveness. In fact, it is also a rough indication of other effects of ultraviolet energy of a spectral range from at least λ2500 to λ3200.

Hess, who pioneered in the study of the prevention and cure of rickets by means of ultraviolet energy, and Anderson [72] exposed two groups of rachitic rats, respectively, to ultraviolet energy of two spectral ranges. Those exposed to energy from λ2500 to λ2800 were cured as readily as those exposed to energy from λ2900 to λ3660.

The latter energy is present in natural sunlight and skylight, but the former energy is only available from some artificial sources.

Bunker[73] found energy of λ2537 to be about 54 percent as effective in inducing healing in rachitic rats as energy of λ2967. Luckiesh and Taylor[26] found energy of λ2537 about 80 percent as effective as energy of λ2967 in producing a

TABLE XXXI

The Relative Antirachitic Effectiveness of Energy of Various Wavelengths as Determined by Bunker with Rats, Compared with the Relative Erythemal Effectiveness as Determined by Luckiesh and Taylor for Average Untanned White Human Skin

Wavelength	*Relative Effectiveness*	
(Angstroms)	*Erythemal*	*Antirachitic*
3022	50	46
2967	100	100
2804	6	70
2652	30	64
2537	80	54

minimum perceptible erythema (MPE) on average untanned white skin. Owing to the lesser penetration of the skin by the energy of shorter wavelength, one might expect the antirachitic effectiveness of λ2537 to be less than that of λ2967.

In Table XXXI the relative erythemal effectiveness of ultraviolet energy as obtained by Luckiesh and Taylor for an MPE on average untanned white skin is compared with Bunker's results of relative healing effect on rachitic rats. It is seen that the relation holds fairly well for λ2537 and λ2967, but not for the wavelengths between these two. Incidentally, as seen in Fig. 28, the average of the results of various investigators indicates the erythemal effectiveness of λ2537 is about 55 percent of that of λ2967. However, the results were obtained by different techniques so that it is questionable that the average of the results has a definite

meaning. It should be emphasized that there are great difficulties involved in obtaining such data, and particularly the relative antirachitic effectiveness of energy of various wavelengths. Therefore, the data presented in Table XXXI are to be considered only as a rough but interesting comparison.

Knudson and Benford[74] irradiated rachitic rats at a distance of 3 feet from a Type S-1 sunlamp in a reflector, a bare 15-watt germicidal source (low-pressure mercury-arc), and a fluorescent or F sunlamp (with E phosphor). They found that the durations of the exposure for a given degree of healing for these sources were, respectively, 50, 20 and 140 minutes. Here again the antirachitic effectiveness of the energy from these sources is roughly proportional to the erythemal effectiveness.

Experiments with germicidal sources in poultry houses for the primary purpose of killing organisms pathogenic to poultry appear to have yielded additional beneficial results by way of antirachitic effectiveness. In other words, they seem to have produced effects similar to those achieved by feeding Vitamin D.

These are mere glimpses of a vast amount of available data which reveal the beneficial effects of ultraviolet energy. Comprehensive treatises have been published by Laurens,[2] Duggar,[3] and Mayer,[4] which include many details of the effects of ultraviolet energy. Obviously, in the use of antirachitic energy one cannot eliminate erythemal energy for their spectral regions are coincident for the most part. For this reason, biologists, physiologists, pediatricians, and others who apply this energy have appraised their dosages in terms of the degree of erythema produced. Little or no thought was given to the effect of sub-erythemal dosages which, as discussed later, are effective in the general conservation of health and in the prevention and cure of specific diseases and disorders.

E-VITONS EMITTED BY VARIOUS SOURCES

As discussed in early chapters, the term *E-viton* is a unit of erythemal flux. It weights radiant energy of various wavelengths according to its effectiveness in producing erythema on average untanned human white skin. The E-viton is analogous to the lumen which weights radiant energy of various wavelengths according to its ability to produce the sensation of brightness. Sources of ultraviolet energy may be rated in E-vitons output just as sources of light are rated in lumens output. An E-viton is equal to 10 microwatts of erythemal flux. This means that an E-viton is equivalent to 10 microwatts of monochromatic energy (about $\lambda 2967$) of maximal erythemal effectiveness, or to 10 microwatts of heterogeneous energy after its components are weighted according to their respective erythemal effectiveness. Erythemal flux means ultraviolet radiant flux that has been properly weighted in accordance with its ability to produce erythema on average untanned skin.

The output of ultraviolet energy from most of the more powerful sources that are available cannot be stated with high accuracy, for it is affected by a number of factors which vary from lamp to lamp. However, if the spectral distribution of energy is known, the energy of various wavelengths can be weighted according to its erythemal effectiveness as presented in Table X or Fig. 30. In Table XXXII the outputs in E-vitons are presented for various sources with the understanding that these are approximate average values at the present time.

Our experience indicates that an exposure of 25 to 50 E-viton-minutes per sq. cm. will generally produce a minimum perceptible erythema MPE on untanned areas of white skin that are commonly exposed in the summer. About 40 E-viton-minutes per sq. cm. is a fairly satisfactory

average. This means 400 microwatt-minutes per sq. cm. of energy of $\lambda 2967$ or equivalent erythemally weighted heterogeneous energy. On the inner skin of the upper arm an MPE dosage is commonly about one-fifth of the foregoing values. As seen in Chapter II, an exposure of average un-

TABLE XXXII

Approximate Erythemal Flux or E-Vitons Emitted by Various Sources of Ultraviolet Energy

Source	Glass	Watts	Output in E-Vitons Total	Per Watt
Sunlamps				
S-1	776	400	68,000	170
S-4	776	100	50,000	500
RS-4	776	100	25,000	250
RS	776	275	25,000	90
Germicidal				
4-watt	9,741	4	33,500	8,375
8-watt	9,741	8	84,000	10,500
15-watt	9,741	15	160,000	10,700
30-watt	9,741	30	400,000	13,300
High-pressure mercury-arcs				
AH-6	774	1,000	1,000,000	1,000
AH-6	quartz	1,000	3,500,000	3,500
Fluorescent or F sunlamps				
40-watt	9,821	40	100,000	2,500
20-watt	9,821	20	45,000	2,250
Tungsten-filament CX lamps				
3,025° K.	Corex D	500	2,000	4

tanned skin for about 20 minutes to noon sunlight on a clear day in June produces an MPE. This means that the intensity of erythemal flux is about 20 microwatts per sq. cm. or 2 E-vitons per sq. cm.

For reasonable exposures to the sunlamps listed in Table XXXII, the eyes need no protection. Ordinary glass affords protection against the short-wave energy emitted by the germicidal sources. Dark goggles are advisable if one is close to the AH-6 lamps, owing to their high intrinsic brightness. As illustrated in Fig. 9, the actual source of

energy in the AH-6 lamp is mercury vapor under high pressure in a quartz capillary tube. This is surrounded by an envelope of special glass or quartz through which water is circulated for cooling the capillary tube. In this case much of the infrared energy is absorbed by the water and is not radiated into the surrounding space. These lamps may be operated without the water jacket if a blast of air is used to cool the capillary tubes.

The fluorescent or F sunlamp is basically a fluorescent lamp with a tube of special glass coated inside with an E (erythemal) phosphor instead of the luminescent phosphors used for the production of light. The E phosphor is excited by the energy of $\lambda 2537$, which is emitted in abundance by the mercury vapor at very low pressure, and it emits radiant energy of longer wavelengths, corresponding to those in the short-wave region of the solar spectrum. It can be made in the same wattages as fluorescent lamps for lighting purposes. As the wattage increases, the length and area of the glass tube increase. Obviously, this means an increase in the area of the E phosphor with a resulting increase in the erythemal flux emitted. Such factors as the thickness of the E phosphor and the composition and thickness of the special glass also determine the output of erythemal flux and the short-wave spectral limit of the emitted energy. For general use, no significant amount of energy of wavelengths shorter than $\lambda 2800$ should be emitted. In fact, this is an important characteristic of a source or an equipment which may be termed a sunlamp.

The tungsten-filament CX lamps have bulbs of special ultraviolet-transmitting glass. The output of erythemal flux is comparatively small compared with that of the other types of sources. However, it is sufficient to produce erythema and a moderate tan of human skin and to prevent and cure rickets in chickens and babies.

If we assume that an exposure of 40 E-viton-minutes per sq. cm. or 400 microwatt-minutes per sq. cm. produces a barely perceptible erythema or MPE on average untanned skin, it is easy to determine either the intensity of erythemal flux or duration of exposure if the value of one is

TABLE XXXIII

Approximate Duration of Exposure to Produce a Minimum Perceptible Erythema MPE on Average Untanned Skin by Average Midday Midsummer Sunlight and by Various Artificial Sources in Efficient Reflectors at a Distance of 24 Inches from the Skin

	Minutes
Summer sunlight	20
Type S-1, 400-watt	4
Type S-4, 100-watt	5
Type RS-4, 100-watt	18
Type RS, 275-watt	6
F-sunlamp, 40-watt	8
Quartz mercury-arc, 360-watt	3
Sunshine carbon arc, 6 mm.	10
Tungsten CX, 500-watt	50
Germicidal, 4-watt	8
Germicidal, 8-watt	5
Germicidal, 15-watt	2.7
Germicidal, 30-watt	0.7
Type AH-6, 774 glass, 1000-watt	0.2
Type AH-6, quartz, 1000-watt	0.05

known. For local use of a given sunlamp, the intensity of erythemal flux on the skin decreases rapidly with the distance from the source. Some values are presented in Table XXXIII for various sunlamps at a distance of 24 inches from the skin compared with average midsummer midday sunlight plus some skylight. The artificial sources are assumed to be used in efficient aluminum reflectors. The reflector is an inherent part of the RS-4 sunlamp. Germicidal sources are not sunlamps in the accepted sense, but they can be used by protecting the eyes with glasses. This is also true of the quartz mercury-arcs.

The values in Table XXXIII are to be considered approximate averages for average normal untanned areas of skin which are commonly exposed outdoors in summer. Incidentally, the susceptibility of apparently average normal skins commonly varies over a range of 1 to 2, but many skins are outside this range. We have tested the reciprocity law over a range of 1 to 16 and found it to hold. Doubtless it fails at extreme limits, but it is practicable and convenient to express the relationship between intensity E and time t as $Et = k =$ dosage or exposure.

For 0.1 MPE
$k = 4$ E-viton-minutes per sq. cm.
For a minimum perceptible erythema, MPE
$k = 40$ E-viton-minutes per sq. cm.
For a vivid erythema
$k = 100$ E-viton-minutes per sq. cm.
For a painful burn
$k = 200$ E-viton-minutes per sq. cm.
For blistering
$k = 400$ E-viton-minutes per sq. cm.

For areas of skin which are not commonly exposed, such as the inner skin of the upper arm, the values of k are commonly one-fifth of the foregoing or even less.

It is well known that the skin of some persons is much less resistant than average normal skins. For those persons, the value of k is appreciably less than for the average of most persons. They may develop a vivid erythema from an exposure which ordinarily develops an MPE. For long exposures to erythemal flux, equivalent dosages from 0.1 MPE to 1 MPE apparently are sufficient for conservation of health. Therefore, it is practicable to supply erythemal energy over areas occupied by human beings so that less than an MPE dosage is received in 8 or 10 hours. In other words, such a dosage should not produce more than a vivid erythema on the more sensitive skins. These comments do

not apply to those relatively few "pathological" skins which are adversely affected by natural daylight outdoors.

RADIANT ENERGY FROM VARIOUS SOURCES

There is increasing interest in applications of ultraviolet energy for various purposes. Therefore, the total radiant flux emitted in various spectral bands by various sources is helpful in designing installations. In Table IV such data are presented for the energy reaching a horizontal plane outdoors during midday on typical clear days in midsummer. In Table XIII, the ultraviolet energy emitted in certain spectral bands is presented for noon sunlight, the 360-watt quartz mercury-arc, Type H-6, S-1, and S-4 sunlamps. In Table XVII is presented the spectral distribution of energy emitted by the quartz mercury-arc, and in Table XXVIII this source is compared with the germicidal low-pressure mercury-arc. In Table XXXIV a summary of data obtained by Forsythe, Adams and Barnes [75] is presented. The ultraviolet spectrum is divided into three parts for various needs, and the infrared spectrum is divided into two parts. Water and flesh transmit the near infrared, $\lambda 7600$ to $\lambda 14{,}000$, fairly well. The visible spectrum from $\lambda 3800$ to $\lambda 7600$ is considered as a single band.

It is evident that electrically excited mercury vapor has been promoted recently to a prominent role in the production of light and ultraviolet energy. For a long time the Cooper-Hewitt mercury-arc and quartz mercury-arcs were specialties, but they aided in the preliminaries which led to greatly increased use of mercury vapor. The Cooper-Hewitt lamp operates at a rather low vapor pressure of about 0.0003 atmosphere. Modern fluorescent lamps and germicidal sources are of the extreme low-pressure type. The familiar quartz mercury-arc operates at a vapor pressure of about one atmosphere. (See Plate XVI.)

The 400-watt AH-1 mercury lamp operates at a vapor pressure of about 1.2 atmospheres. The mercury-arc is contained in an inner bulb which is enclosed in an outer bulb to maintain the mercury vapor at a proper temperature.

TABLE XXXIV

Watts Radiated in Various Spectral Regions by Various Sources of Radiant Energy

Source	Watts Input	Total Lumens	*Watts Radiated in Various Spectral Regions* Below 2,800	2,800 to 3,165	3,165 to 3,800	3,800 to 7,600	7,600 to 14,000	14,000 to 26,000
AH-1	400	16,000	0	0.001	4.3	44	21.9	26.9
AH-4	100	3,000	0	0.03	2.3	12	61.1	10.8
AH-6, quartz	1,000	67,000	21.0	87	124	377	93	25
AH-9	3,000	120,000	0	0	22	368	......	.....
Sunlamps								
S-1	400	7,200	0.01	2.7	5.0	45	86	85
S-4	100	3,000	0.01	0.9	3.6	12	6	11
RS-4	100	2,900	0.01	1.6	3.3	11	......	.....
Fluorescent	40	200	0.01	3.1	7.2	0.9	......	.....
Fluorescent lamps								
40-watt, 3,500° K.	40	2,100	0	0.015	0.1	7.3	0.07	nil
40-watt, 6,500° K.	40	1,800	0	0.02	0.3	7.5	0.05	nil
100-watt, 3,500° K.	100	4,200	0	0.03	0.2	14.6	0.14	nil
100-watt, 6,500° K.	100	3,700	0	0.04	0.7	15.5	0.10	nil
Tungsten-filament lamps								
40-watt, 2,500° K.	40	465	0	0	0.015	3.03	13.2	11
100-watt, 2,750° K.	100	1,600	0	0	0.06	9.9	36.0	29
500-watt, 2,950° K.	500	9,850	0	0.01	0.53	60	205	155
1,000-watt, 3,000° K.	1,000	21,000	0	0.04	1.04	125	410	330
Germicidal sources								
8-watt	8	27	1.5	0.03	0.03	0.14	nil	nil
15-watt	15	53	2.9	0.06	0.05	0.26	nil	nil
30-watt	30	132	7.3	0.16	0.13	0.65	nil	nil

The 100-watt AH-4 mercury lamp operates in an inner tube of quartz at a vapor pressure of about 8 atmospheres. It contains an outer envelope of glass. This lamp provides the basis of the S-4 sunlamp which contains an outer envelope of special glass with a short-wave cut-off at λ2800. The RS sunlamp has a filament ballast and is self-contained so that it can be used in any ordinary socket on a lighting circuit.

Pioneering work on really high-pressure mercury-arcs has been done by C. Bol.[76] The mercury is confined in a

quartz capillary tube and when operating the vapor pressure is many atmospheres in the AH-6 lamp. The water-cooled AH-6 lamp is illustrated in Fig. 9. A cluster of them, illustrated in Fig. 93, provides an extremely powerful source

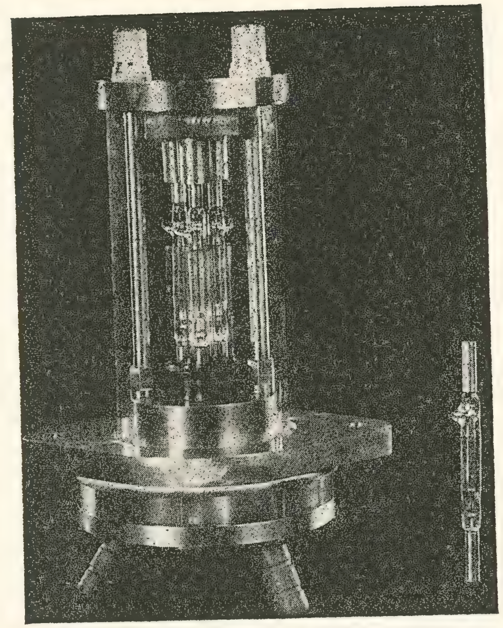


Fig. 93. A cluster of high-pressure water-cooled mercury-arcs. An individual quartz capillary tube is illustrated at the right.

of light and of ultraviolet energy. The extent of the latter spectrum depends upon the composition of the outer flow-tube in the water-cooled type. It may be of quartz, pyrex or other special glass. The AH-6 lamp is also used without the outer envelope in which case the quartz capillary mercury-tube is cooled with a blast of air.

As the vapor pressure is increased, a continuous spectrum develops and the typical line-spectrum of mercury is gradually submerged. This is illustrated in Fig. 94 for four

different vapor pressures namely: 54, 102, 197 and 319 atmospheres. Bol has operated such a source in the laboratory at pressures up to 1000 atmospheres by surrounding

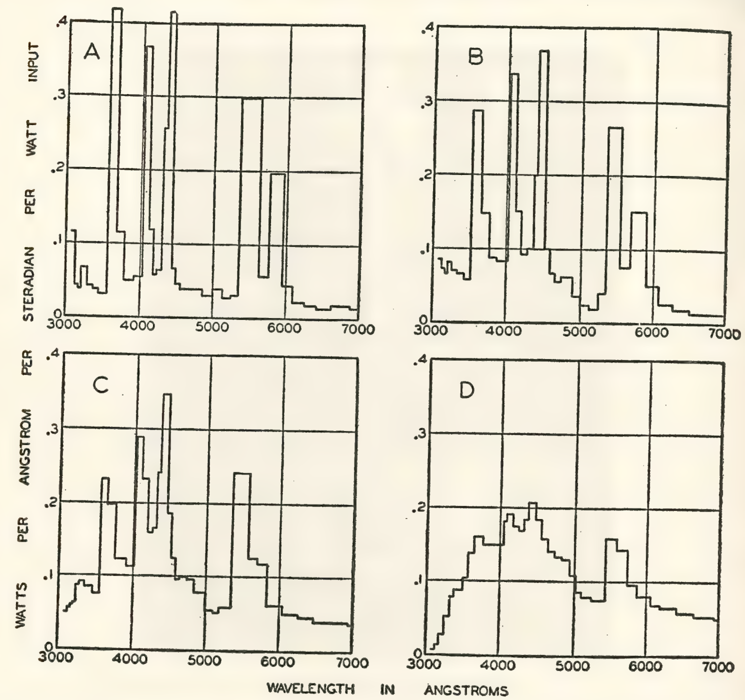


FIG. 94. Illustrating the effect of the mercury-vapor pressure on the spectral distribution of the energy emitted, *A*, 54 atmospheres; *B*, 102; *C*, 197; and *D*, 319 atmospheres.

the capillary quartz tube with water at very high pressures. Whether the higher pressures become practicable is a matter of future development. The spectral distribution of energy emitted by the AH-6 water-cooled lamp at the present time approximates that in *B* Fig. 94.

It is obvious that the variety of sources available makes possible various kinds and intensities of artificial sunlight

for a variety of present and future applications. Purely localized needs may be met with standard sunlamps or with special equipment using the more powerful sources to provide very high intensities of energy. Large areas may be supplied with adequate artificial light supplemented with appropriate intensities of ultraviolet energy for health.[77] Other areas may be provided with intensities of light and radiant energy simulating sunlight. These possibilities are so new and varied that only glimpses of them are presented in this book. However, adequate data and principles are available for designing artificial sunlight specifically for any purpose.

A POWERFUL IRRADIATION CHAMBER

An example of the present possibilities in providing extremely powerful and controllable artificial sunlight for local applications is an irradiation chamber[78] built for a specific purpose. However, such equipment has many possibilities in therapy and other fields. Water-cooled AH-6 mercury lamps are used which have the decided advantage of having much of the infrared energy carried away by the circulating water. Major details are illustrated in the vertical sections of Fig. 95. The end-view reveals two parabolic sections with AH-6 lamps installed in the longitudinal foci. Four lamps are installed in the upper section and two in the lower one. Near these sources *S* the inner wall is lined with aluminum *R* which efficiently reflects visible and ultraviolet energy. The other areas of the interior are coated with a highly reflecting aluminum paint *P*. The chamber is long enough to admit an adult person on a stretcher, having a minimum of supporting straps so as to interfere as little as possible with the radiant energy from below. The lower portion, containing transformers, relays, etc., is enclosed with perforated metal panels.

The intensity of illumination at the center of the chamber is about 25,000 footcandles. An appreciation of this magnitude is obtained by comparing it with the intensity of illumination outdoors at noon on clear days in summer, which is about 9000 footcandles. Naked human beings can be exposed without discomfort to this extremely

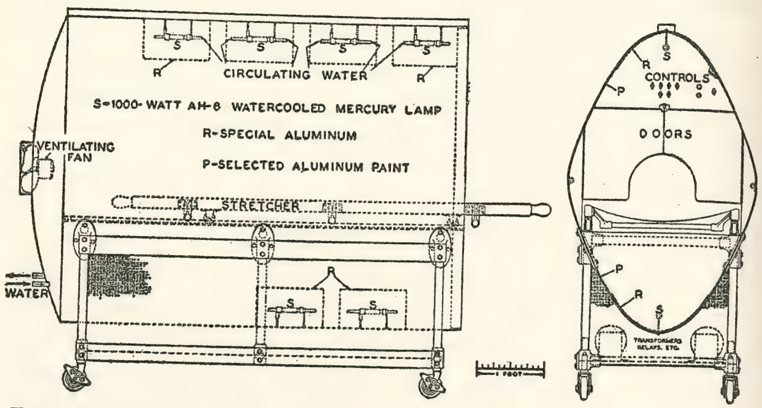


FIG. 95. Diagrammatic vertical sections of a powerful irradiation chamber containing six AH-6 quartz high-pressure mercury-arcs with pyrex flow-tubes for circulating water.

high intensity of illumination. The light derives its "coolness" from both the high luminous efficiency of the sources, about 65 lumens per watt, and the dissipation of more than two-thirds of the radiant energy in the flowing water which is used to cool the sources. The resultant light is more than twice as cool as sunlight for equal footcandles. In the irradiation chamber a flow of water approximating two gallons per minute is sufficient for cooling the six lamps.

Each lamp in the chamber is controlled by a switch on the outside front panel so that any desired number of lamps may be used. The automatic control-system is such that the lamps do not receive any energy until water is flowing in

the cooling system. Also if a lamp fails during operation, all the lamps are automatically switched off and the flow of water ceases.

Lamps with outer jackets or flow-tubes of heat-resisting 774 glass are used in this case so that the emitted radiant energy is confined to the spectral range of sunlight. The extent of the spectrum can be controlled by cylindrical filters of glass of various spectral transmission characteristics. Some of these could be slipped over the flow-tube. Smaller cylindrical filters can be slipped over the inner quartz capillary tube which contains the actual source of radiant energy. In this location the filter is inside the quartz flow-tube and is cooled by the flowing water. This location was found to be necessary when using a Corning 587 heat-resisting red-purple ultraviolet-transmitting glass tube which absorbs nearly all the visible energy and transmits the long-wave or near-ultraviolet energy. The flowing water cools this special inner filter and removes a much larger percentage of radiant energy than when no inner filter is used. Therefore, extremely high intensities of long-wave ultraviolet energy can be obtained with relatively little heating effect upon the subject.

Various filters can be used, depending upon the purpose. Spectrograms showing the spectral extent of their transmissions and actually made in the chamber are illustrated in Fig. 96 for certain filters and combinations listed in Table XXXV. It will be noted that no significant energy beyond the short-wave limit of the solar spectrum is transmitted by any of the filters. In Table XXXV the average intensities of energy were measured on a horizontal plane about seven inches above the stretcher or central plane of the chamber with the various filters in place as indicated. The filters were obtained from the Corning Glass Works and bear the supplier's identifications.

It is seen that when no filters are used and all six sources are operating, average untanned skin receives an MPE dosage in about 1.5 minutes. However, a naked person is exposing areas of skin that are not commonly

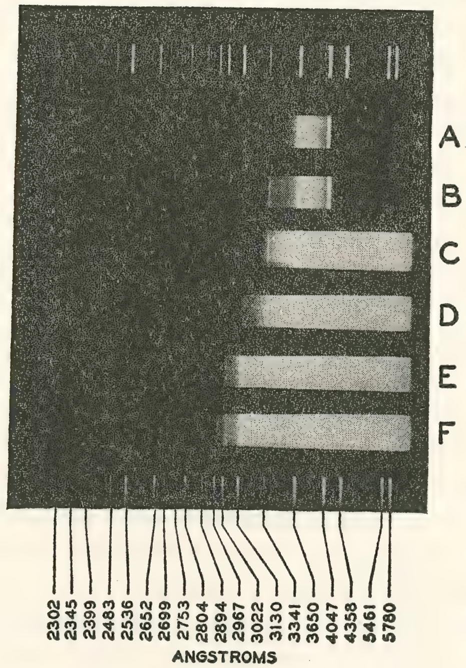


Fig. 96. Spectrograms made in the irradiation chamber (Fig. 95) with various filters and combinations as identified in Table XXXV.

exposed and some of these areas are less resistant to erythemal flux. Therefore, the time required to provide an MPE dosage is less than that given in Table XXXV for some areas of skin. The intensities of erythemal flux in the fifth column are expressed in microwatts per sq. cm. of energy equivalent to λ2967 in the production of erythema.

When inner filter 587 and outer filter 172 AJ are used simultaneously, an average naked human subject could

remain in the chamber with no discomfort for an hour or two without receiving much of an erythema on the tenderest skin. With the inner filter 587 and no outer filter, the short-wave limit of emitted energy is extended somewhat. This results in a great increase in erythemal effect, but very little change in radiant heat or heating effect. In

TABLE XXXV

Intensities of Ultraviolet Energy and Erythemal Flux Obtained in an Irradiation Chamber with Six AH-6 Mercury Lamps with Pyrex Flow-Tubes and Various Filters

	Filter		Microwatts per Sq. Cm.		Minutes
			Approximate	*Erythemal*	*for*
Fig. 96	*Outer*	*Inner*	*λ3,600 to λ4,000*	*Flux*	*MPE*
A	587	172 AJ	1,600	1.6	250
B	587	None	2,500	18	23
C	None	772	5,700	2.5	165
D	None	172 AJ	7,200	18.5	22
E	None	774 Pyrex	9,200	110	4
F	None	None	10,600	240	1–2
	Summer sunlight		2,500	20	15–20

these cases the emitted energy is almost entirely confined to the ultraviolet spectral region. When the inner filters are in use on all six sources, both the light and heat are greatly reduced. Under these conditions the six sources radiate approximately 400 watts into the chamber and it is not necessary to operate the ventilating fan which is installed in the rear end as illustrated in Fig. 95. When the inner filters are not used, about 2300 watts are radiated into the chamber by the six sources. Under this condition the ventilating fan makes the environment comfortable for human subjects.

From the comments and data presented, it is seen that extensive control of great intensities of ultraviolet, visible and infrared radiant energy is possible. The maximum intensity of visible energy is about 3 times that of the best June sunlight, and can be obtained with or without ery-

thema and without undue discomfort to a human subject. The erythemal effectiveness varies throughout a wide range, and the maximum is about 10 times that of the best summer sunlight. Tanning can be obtained with moderate erythema. The powerfulness and flexibility of control are ideal for physiological researches and therapeutic applications in the realm of radiant energy. Obviously such a chamber can be variously modified for other investigations of many other processes and for the testing of materials. It represents one of the outstanding challenges of the sun and it should challenge those interested in the effects of radiant energy in many specific fields. Nothing comparable in intensity, controllability and convenience has been available heretofore.

SIMULATING OUTDOOR DAYLIGHT

When one is asked to recommend artificial sources of radiant energy in order to simulate outdoor sunlight, he finds adequate data available for combining various sources, if necessary, to meet the requirements. However, several questions arise as to the basis of the requirements. Why should noon sunlight on a clear day be considered basic? Shall skylight with its abundance of erythemal and antirachitic energy be ignored? If not, the problem becomes one of simulating outdoor daylight; but this varies greatly with latitude and throughout the day and year. The intensity of visible energy, as measured in lumens per square foot (footcandles), obviously varies with the seasons. The intensity of erythemal energy, measured in E-vitons per sq. cm., is even more variable with the seasons. Viewed spectrally, daily, seasonally and geographically, outdoor daylight is so variable that it is difficult to decide upon overall averages. In any case, the spectrum of artificial sunlight or daylight must not extend significantly beyond

$\lambda 2900$, the approximate short-wave limit of the solar spectrum.

In Fig. 24 it is seen that from a 6-year continuous record, the total erythemally-effective ultraviolet energy in December is about one percent of the total for the year. The month of January contributes less than 2 percent of the year's total. On the other hand, the two months of June and July contribute a third of the total for the entire year. Of course, this difference between summer and winter is partly accounted for by the difference in the daily duration of daylight. However, on making allowances for this the average intensity of erythemal energy at the earth's surface is about 10 times greater in midsummer than in midwinter for much of the area of the United States.

During midsummer the intensity of visible energy, measured in footcandles, is only about twice as great as in midwinter. The maximum intensity of sunlight and skylight on a horizontal surface is in the neighborhood of 9000 footcandles. An average during the daylight hours for the entire year is in the neighborhood of 2000 footcandles.

From Chapter II it is seen that a fairly approximate daily average of erythemal dosage at the earth's surface is 8 E-viton-hours per sq. cm. Assuming a daily average of 12 hours of daylight, this amounts to an average dosage of 40 E-viton-minutes per sq. cm. for each hour. In other words, a fair average dosage at the earth's surface is about one MPE each hour for average untanned skin. As seen later, one-tenth of this value appears to be an effective daily dosage for the prevention and cure of rickets.

The intensity of energy of various spectral ranges in any case will be determined by the requirements. Human beings like midsummer sunlight when lying on the beach for restricted periods. They like it for playing golf and for other outdoor recreation. They would scarcely choose to

live and work all day under such an intensity as outdoor noon sunlight on a clear day in June. At least they would prefer the daily average to the daily maximum. If human beings are not involved, it is quite justifiable to simulate intense sunlight or daylight throughout the ultraviolet, visible and infrared regions, by combining various sources.

Combinations of equal numbers of 500-watt tungsten-filament lamps and 1000-watt water-cooled AH-6 lamps with pyrex flow-tubes can simulate summer sunlight fairly well in spectral character at any intensity. Such an installation averaging 100 watts per sq. ft. of area provides an intense artificial sunlight.

Combinations can be built on a basis of 40-watt or 100-watt F lamps by adding some AH-9 lamps, more tungsten-filament lamps and supplying the erythemal energy by means of RS sunlamps or F sunlamps. The latter are basically fluorescent lamps coated with the E phosphor instead of the ordinary luminous phosphors.

There being no standardized requirements, it appears futile to discuss combinations. These can readily be determined for a given need. However, where human beings are involved for long periods at their daily activities, the problem becomes specific. Indoors they might well have whatever benefits there are in outdoor sunlight or daylight. For more than three decades the author has had as one of his objectives the simultaneous supply of radiant energy for health and light for seeing. Such applications from the viewpoint of human welfare are discussed later. Their practicability is based largely upon the effectiveness of sub-erythemal dosages.

SUB-ERYTHEMAL DOSAGES

Many years ago when it appeared that the development of artificial sources of ultraviolet energy was approaching

the stage of general application of biologically-effective ultraviolet energy, the author initiated investigations of the efficacy of sub-erythemal dosages of biologically-effective ultraviolet energy. There appeared to be no reason why the skin had to be exposed sufficiently to develop an erythema in order to achieve antirachitic results. The production of Vitamin D appeared to be a matter of sufficient exposure of the fatty substances in the skin. In fact, there was evidence that fowl were benefited by irradiation of the oil in the feathers and furry animals were benefited by irradiation of the oil in the fur. In fact, there were adequate reasons for suspecting that sub-erythemal dosages were sufficient to prevent and cure rickets. Various researches eventually proved this to be true. These have been discussed elsewhere [1] in detail. Therefore only a few highlights are presented here.

During several years of cooperative researches under the direction of H. J. Gerstenberger, outstanding authority in pediatrics, it was conclusively proved that sub-erythemal dosages cured and prevented rickets in babies. It was also shown that the relatively small amounts of erythemal energy supplied by tungsten-filament CX lamps cured infantile rickets.[22] Dosages one-tenth of those necessary to produce an MPE on average untanned skin prevented and cured rickets in infants. This means that daily dosages at least as small as 4 E-viton-minutes per sq. cm., or 40 microwatt-minutes per sq. cm. of erythemally weighted energy, are antirachitic.

Gerstenberger and Horesh [22] exposed three moderately severe rachitic infants (two Negroes and one white) to 75 footcandles obtained from a 500-watt tungsten CX lamp for 12 hours daily. The type and degree of rickets had been previously established during an observation period of about four weeks. These infants were cured in three months

by these daily sub-erythemal dosages. The 500-watt CX lamp in an oxidized aluminum reflector operated at a temperature of 3035° K. and emitted 0.02 percent of its total output, or 100 milliwatts, in the spectral region from λ2800 to λ3200. The daily exposure was approximately one-seventh of an MPE dosage. Expressed in another way, the daily exposure was 900 footcandle-hours. The dosage or exposure for the three months totaled 13 MPE or 81,000 footcandle-hours.

These results in the cure of rachitic infants were obtained with babies practically fully clothed. Only the head, neck and lower portions of the arms and legs were exposed. A mild tan was produced on white skin, but obviously there was no erythema. These facts are important from the author's viewpoint, particularly when combined with the established effectiveness of sub-erythemal dosages. They revealed the practicability of applications of erythmal energy similar to, or a part of, lighting installations over large areas occupied by human beings in classrooms, work-places and elsewhere.

Other encouraging evidence of the efficacy of sub-erythemal dosages was forthcoming. Dutcher and Honeywell [79] found that an intensity of about 10 footcandles supplied by a regular 100-watt tungsten-filament lamp with an ordinary glass bulb produced a definite antirachitic effect on rats. When this illumination was applied 8 hours each day for 21 days, the percent of bone ash was twice that for rats similarly fed but confined in darkness. When this illumination was applied continuously for 35 days, the percentage of bone ash was about three times that obtained from rats similarly fed but confined in darkness. Even the light used in the laboratory produced a measurable effect. It should be noted that the thin ordinary glass of the bulb of a tungsten-filament lamp transmits a slight amount of

energy of λ3000 and also measurable amounts of energy of longer wavelengths. Obviously, these results indicate a low threshold value of biologically-effective ultraviolet energy.

The tungsten-filament CX lamps were developed on the basis of the author's analyses which were supported eventually by clinical evidence. These lamps have been extensively used in brooders for baby chicks and to some extent in incubators for babies. Maughn [80] proved that baby chicks developed free of rickets when heated and irradiated in a brooder with a 60-watt tungsten CX lamp without exposure to natural daylight and without being fed any special antirachitic food.

In another investigation, Maughn used a 500-watt tungsten CX lamp which supplied 50 footcandles for 5 hours each day. Chickens were fed upon a restricted diet until they were suffering from severe rickets. Control chickens were similarly fed but were not exposed to light. Appraisals by six methods—general appearance, growth, post-mortem, X-ray photographs, blood calcium, and bone ash—all showed significant effects of the radiant energy from the 500-watt tungsten CX lamp. It should be emphasized that these chickens were suffering from severe rickets, and it is logical to assume that prevention of rickets requires smaller dosages than cure of severe rickets. Huldschinsky [81] in a paper on the prophylactic use of ultraviolet energy concludes that only one-tenth of a curative dosage is necessary to prevent rickets. He also expresses the belief that mild sources and dosages of ultraviolet energy are most desirable prophylactics against rickets.

Such evidence leads directly to an interest in providing low intensities of erythemal energy for long periods by means of lighting or supplementary sources where human beings are confined indoors. Particularly during winter months they are exposed little, if at all, to natural daylight

outdoors. It is fairly well established that ordinary window-glass, owing to its thickness as well as to its composition, does not transmit much antirachitic energy. Unless direct sunlight is admitted by a window, such energy must come indoors from a relatively small area of sky. As a consequence, human beings indoors must generally receive their biologically-effective radiant energy from artificial sources if they are to receive any during much of the year in higher latitudes.

In this connection it is interesting to appraise the intensity of short-wave ultraviolet energy present in 20 footcandles of illumination from a 500-watt tungsten CX lamp operating at a color-temperature of about 3000° K. For each footcandle, the radiant flux shorter than $\lambda 3100$ would be about 0.0083 microwatt per sq. cm. if the bulb were quartz. However, the special bulb transmits only about half the energy shorter than $\lambda 3100$. Therefore, the total intensity of radiant flux shorter than $\lambda 3100$ present in 20 footcandles produced by energy radiated directly from the 500-watt CX lamp is about 0.08 microwatt per sq. cm. Operating for 5 hours daily, the dosage of this energy would be about 0.4 microwatt-hour per sq. cm. or 24 microwatt-minutes per sq. cm.

It will be noted that this energy has not been weighted according to its erythemal effectiveness. When it is so weighted, the daily dosage is equivalent to about 4 percent of an MPE dosage. Considering that this caused a significant improvement in severe rickets in chickens, it is seen that very small fractions of an MPE dosage are biologically effective.

There are two other aspects which are of interest. The effect of a single dosage of erythemal energy on a rachitic baby can be noted by the skilled observer for several weeks afterward. Gerstenberger and Russell [82] have shown that

erythema-producing exposures to an S-1 sunlamp once a week resulted in the cure of rachitic babies. In two weeks a decided improvement was evident in the blood calcium and inorganic phosphate level. The normal values were reached in 5 to 7 weeks; that is, with 5 to 7 weekly erythemal dosages.

The other aspect is the total area of skin that is exposed to the biologically-effective energy. It has been proved that only those areas of skin that are commonly exposed by children in classrooms and adults at work are sufficient. Inasmuch as the effects of successive dosages are cumulative, it is not surprising that very small daily dosages suffice to cure rickets and that even smaller dosages are adequate for normally healthy or near-healthy animals, human babies, children and adults. However, the growing animal or child must appropriate for growth as well as for maintenance. This is one reason why rickets are common among young children and not among adults. Nevertheless the same physiological processes are at work in adults, so that what benefits growing animals and children must benefit adults.

These are glimpses of aspects of great importance in "bringing the outdoors indoors" for the benefit of both mankind and the animal kingdom.

INSTALLATIONS IN OCCUPIED INTERIORS

Any light-source which simultaneously emits light and erythemal energy can be used to supply radiant energy for health and light for seeing. The sun and sky are light-sources of this dual nature. A quartz mercury-arc properly filtered with a suitable ultraviolet-transmitting bulb is such a source, but the spectral character of the light is not generally acceptable. The tungsten-filament CX lamp emits suitable light, but insufficient ultraviolet energy to be prac-

ticable for general use. The S-1 sunlamp when it first appeared was used for dual-purpose lighting[84] to some extent, but it is not ideal for the purpose. The modern fluorescent lamp could be equipped with a tube of special glass and different areas of the bulb could be coated with the E-phosphor and the luminous phosphors. However, from an economic viewpoint it now appears that a lighting installation of fluorescent lamps supplemented with sunlamps would constitute best practice at the present time.

Before discussing this combination let us compare the erythemal effectiveness of some of the light-sources. In Table XXXVI are presented the approximate exposures in footcandle-hours which produce an MPE on average untanned white skin.

TABLE XXXVI

Approximate Exposures in Footcandle-Hours to Supply an MPE Dosage and Relative Erythemal Effectiveness of Various Light-Sources

Light-Source	*Footcandle-Hours for MPE Dosage*	*Relative Erythemal Effectiveness per Footcandle*
Quartz mercury-arc, new	6	420
With pyrex 1 mm. filter	35	70
Quartz mercury-arc, old	12	210
Arc, sunshine carbons	90	28
Type S-1 sunlamp	67	37
RS and RS-4 sunlamps	60	42
Tungsten, 500-watt CX	2,000	1.2
Fluorescent lamp, 6,500° K	4,170	0.6
Fluorescent lamp, 3,500° K	9,500	0.26
Summer sunlight	6,000	0.43
Summer skylight, clear days	830	3
Summer sunlight plus skylight	2,500	1
Winter sunlight plus skylight	25,000	0.1

Compared in this manner, it is seen that summer sunlight is relatively weak erythemally and that skylight on a clear day is much more effective. Sunlight plus skylight on a clear day in midwinter is about one-tenth as effective erythemally as in summer.

The tungsten-filament CX lamp had a bulb of Corex D glass. The tests were made on 9 subjects at an intensity of 2420 footcandles. The average time required to produce an MPE was 50 minutes. Owing to the heat, the skin was wet with perspiration and, therefore, was more susceptible to the erythemal energy. Therefore, the exposure of 2000 footcandle-hours to produce an MPE should be about doubled for normally dry skin.

The design of a dual-purpose lighting system would be a simple matter if each lumen of light emitted by a suitable light-source were accompanied by the proper amount of erythemal energy. If this were a fixed amount, the designer would find that for a given period of exposure the footcandle-level would be fixed. For example, if 50 footcandles resulted in an MPE in 4 hours, he would have to reduce the level of illumination to about 25 footcandles for an 8-hour work-period in order to limit the exposure to one MPE. Obviously, if the lumens and E-vitons are supplied by different sources there is complete flexibility in design.

There is another aspect of great practical importance. Most surfaces do not reflect erythemal energy efficiently. For this reason this energy can best be utilized by sending it directly downward to the occupied area. The lumens can be directed upward and downward as is necessary in order to provide good seeing conditions. Paints can be made which reflect erythemal energy fairly efficiently, and it is possible that some indirect and direct-indirect installations of artificial sunlight may be made. However, the most practical method is to confine the sunlamps to direct-lighting units. (See Plate X.)

In Fig. 97 is illustrated the original drawing of a dual-purpose fixture which has hung over the author's desk for nearly a score of years. In the center is an S-1 sunlamp

whose light and radiant energy are directed downward. This contributes nearly 100 footcandles to the top of the desk underneath. A definite erythema is produced on the face of the occupant in about an hour. There being a single

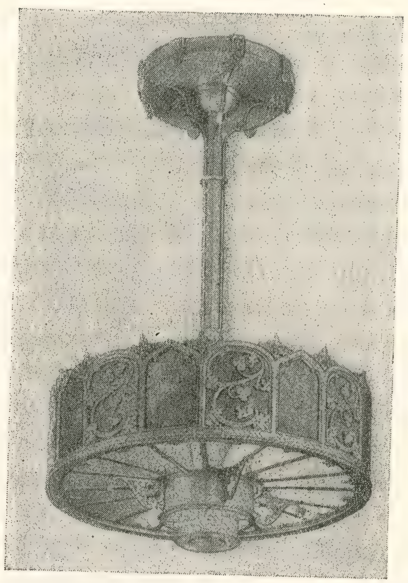


Fig. 97. A dual-purpose fixture which provides a direct component of light and erythemal energy from an S-1 sunlamp and an indirect component from tungsten-filament lamps. Now the RS sunlamps can be used for this localized artificial sunlight.

occupant, this sunlamp can be turned on or off at any time. The lighting due to the sunlamp alone is harsh, but it is softened by a powerful indirect component of light from the same fixture aided by a suitable desk lamp. This and many other fixtures were designed and installed with Type S-1 sunlamps[1] combined with tungsten-filament lamps. Now the RS or RS-4 sunlamps may be used where localized artificial sunlight is desired. However, the F sunlamps can be combined with F lamps to provide erythemal energy for

health along with light for seeing for large or small areas occupied for long periods. Glare can be more readily avoided by their use.

In designing a lighting system, one deals with the output of the sources in lumens and delivers the desired lumens on each square foot of the work-plane. In considering sunlamps, E-vitons are handled in the same manner excepting that time, or duration of exposure, must be taken into account. If one wishes to confine the total dosage to the equivalent of one MPE on average untanned skin, it is only necessary to remember that a dosage of 40 E-viton-minutes per sq. cm., or ⅔ E-viton-hour per sq. cm. produces an MPE. This is equivalent to about 600 E-viton-hours per sq. ft. By dividing this value by the hours of exposure, the intensity of erythemal energy in E-vitons per sq. ft. is obtained for a dosage equivalent to an MPE on average untanned skin. As emphasized elsewhere, we have found that for skin moistened by perspiration, as it often is in summer, an MPE dosage may be 25 or 30 instead of 40 E-viton-minutes per sq. cm.

If the installation is designed for different periods of exposure, the intensities of erythemal flux in E-vitons per sq. ft. to provide an MPE dosage are as follows:

For 8 hours, about 75 E-vitons per sq. ft.
For 6 hours, about 100 E-vitons per sq. ft.
For 4 hours, about 150 E-vitons per sq. ft.
For 2 hours, about 300 E-vitons per sq. ft.

If a total dosage equivalent to only 0.1 MPE is desired the foregoing intensities of erythemal flux should be reduced to one-tenth of their values. These would be, respectively, 7.5, 10, 15 and 30 E-vitons per sq. ft. Any intensities between these two sets of values should be safe for persons with skins of reasonably normal sensitivity. In other words, the variation in skins is fairly well taken care of by keeping

the maximum total dosage below an MPE dosage for average skins. The more sensitive skins would not develop more than a vivid erythema. Gradually this would result in tanning of most skins. Those relatively few persons whose skins are particularly sensitive could find ways of reducing their exposure.

THE FIELD OF ANIMAL HUSBANDRY

In some ways mankind has given more attention to animals than to human beings. Therefore, it is not surprising that many applications of artificial sunlight have been made in poultry houses and elsewhere. Investigations have shown that chicks are healthier and grow more rapidly under the influence of ultraviolet energy. Sunlamps appear to compete favorably with cod-liver oil. The new germicidal sources are now in use to reduce disease, and apparently they are also directly beneficial to growing fowl by preventing rickets and otherwise promoting health and growth. The RS and RS-4 sunlamps are practicable in poultry houses and are being experimented with where other animals are housed. Here again some believe that the new germicidal sources will serve the dual purpose of killing micro-organisms that are pathogenic to poultry and other animals and of preventing rickets and promoting health in other ways. In such applications the possible deleterious effects such as conjunctivitis and severe erythema should be kept in mind. Certainly with the variety of sources of radiant energy now available, the field of animal husbandry appears to be extensive.

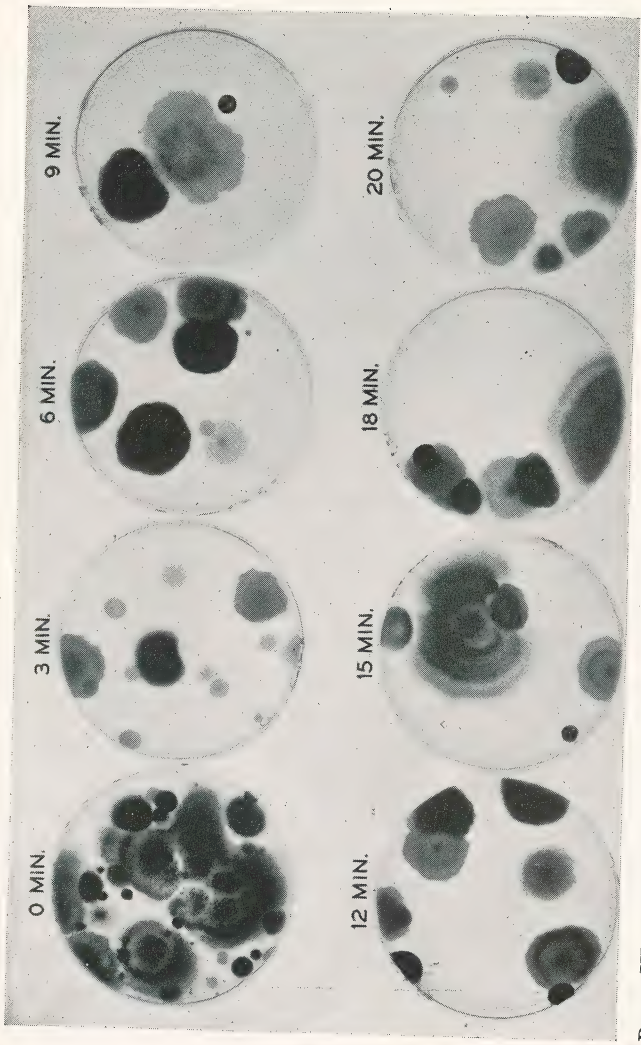


PLATE XI. Wort Agar in petri dishes infected with water in which old peat moss had soaked was irradiated with an intensity of germicidal flux of 200 microwatts per sq. cm. for the number of minutes indicated in each case. After incubation it is seen that many organisms were killed in 3 minutes or less. Some survived an irradiation of 20 minutes or an exposure of *4000* microwatt-minutes per sq. cm.

Chapter XI

Fading of Materials

MANY MATERIALS are altered in one way or another by the action of radiant energy. Probably all dyed textiles fade to some extent if exposed to daylight or artificial light for a sufficient length of time. Paints and wallpapers are likewise susceptible. Ordinary glass commonly acquires a purplish tint after long exposure to outdoor sunlight. Glass envelopes used with arc-lamps exhibit this characteristic.[85] Clear ultraviolet-transmitting glasses "solarize" when exposed sufficiently to radiant energy rich in short-wave ultraviolet energy. Heating these glasses at a sufficient temperature will generally decolorize or desolarize them.[1] Plastics are not immune. Some white ones will acquire a brownish or purplish color after sufficient exposure to ultraviolet energy, particularly of the shorter wavelengths. The problems of fading of materials have always been present, but they are growing more important with increasing levels of illumination with artificial light and with increasing use of ultraviolet energy.

Fastness or permanency is a relative matter. Perhaps no dyed textile or colored paint is unsusceptible to radiant energy in the ultraviolet and most of the visible spectral regions. Permanency is somewhat related to simplicity in chemical composition. It is definitely related to the degree of imperviousness. An elementary material is generally more permanent than a complex compound or a mixture of compounds. A vitrified colored enamel resists fading where a colored textile or paint does not. An aluminum surface is relatively stable, but an aluminum paint may be significantly affected by short-wave ultraviolet energy.

Fugitive colors in textiles, wallpapers and paints, and lack of permanency in physical characteristics of other materials, are nuisances that are often disturbing and sometimes costly. Radiant energy is blamed as the offender without adequately recognizing that the responsibility for fastness or permanency should actually rest upon the materials. Nevertheless through understanding of the relationships between radiant energy and permanency, better materials will be produced and some safeguards will be recognized in the use of light and radiant energy.

Study and discussion of fading are fraught with difficulties. There are no standard materials, and the identification of materials is generally inadequate. There are countless materials and many combinations of them. Each must be tested individually in order to obtain specific data. However, it is possible to develop principles and generalizations which are useful provided it is recognized that there may be many exceptions among the great number and variety of materials. Here the subject is treated largely from the viewpoint of dyed materials. These are not only important in themselves, but colors obtained in this manner, being generally more fugitive, are the more practicable for establishing certain fundamental principles and generalizations.

Various individuals and organizations have contributed much to our knowledge of fading, and some pertinent facts and principles established by them are mentioned in the discussions which follow. Most of these investigations have had for their objective improvements in fastness and elimination of particularly fugitive coloring materials. On the other hand, the investigations of the author and his colleagues, particularly A. H. Taylor, have had for their primary objective the relationship of visible and ultraviolet energy to the fastness of dyed materials and to the permanency of materials in general. For this reason this discussion deals primarily with consecutive investigations of Luckiesh and Taylor [86] for more than a score of years. The chapters dealing with reflectance and transmittance of materials are of some interest in this connection.

VARIOUS FACTORS IN FADING

Fading is a complex photochemical reaction influenced by numerous factors. Some of the more important ones are intensity of radiant energy at the surface of the material, the spectral character of the light or radiant energy, the duration of exposure, the temperature of the material, atmospheric humidity and contamination, degree of access of air, the character of the material containing the coloring material, the method of applying the coloring as in the case of dyes and, of course, the coloring medium itself. Any investigation of fading of particularly sensitive materials, such as dyed textiles, becomes the more complex due to the difficulties in controlling some of the factors. Some extensive investigations of these factors have been made.[93] Manufacturers of paints and other colored materials conduct tests more or less continuously. The primary objectives of most of these investigations are to determine the fastness of specific dyes and paints when exposed to daylight and the outdoor elements, to develop methods of making accelerated tests, and to improve products by selection or otherwise.

In the present discussion we are primarily interested in fading and permanency indoors where the environment is less variable and some of the factors are fairly well suppressed. This simplifies matters somewhat, but we are still handicapped by the lack of standard materials and of methods of identification. However, out of this maze some principles and generalizations have been established which are useful in applications of light and radiant energy.

Indoors some of the factors which affect fading are reduced to minor importance. For example, duplicate specimens of dyed textiles exposed in normally dry and humid air faded at approximately the same rate. The rate of fading was found to be practically the same at 85° F. and 120° F., but it was measurably more rapid at 150° F. These conditions include the ranges usually encountered indoors excepting where a material is abnormally heated or illuminated as, for example, by being very close to a powerful light-source.

Excessive moisture and air abnormally contaminated with active gases are sometimes encountered indoors. Light has been erroneously blamed for the fading they caused. For example, bolts of cloth, the edges of which were exposed to light, showed fading through a large number of folds and the artificial light was emphatically but unjustly indicted. To clear up the matter, unfaded specimens of the cloth were exposed 1000 hours to 100 footcandles supplied by the same illuminant and they did not fade materially. It was eventually ascertained that the original fading of the ends of the bolts of cloth was due to excessive moisture resulting from combustion of gas in the local heating device. This may have been aided by contaminating gases.

In another common case a young lady insisted that pleated cuffs of very dark blue filmy material on her dress faded decidedly after fluorescent lamps had been installed in her work-room. Examination of the pleated cuffs revealed uniform fading throughout, even in the depths of the pleats. This in itself was evidence that light was not the culprit, but the young lady was insistent and fluorescent lighting was condemned. However, systematic exposure of some of the same material revealed that it was unaffected by exposures to fluorescent light enormously greater than those under which the pleated cuffs were supposed to have

faded. Fluorescent light was exonerated and the young lady was suspected of having cleaned the cuffs in some manner which caused them to fade uniformly. Human nature is involved in many ways in complaints of fading.

These are examples of erroneously indicting the most obvious factor and of the unreliability of diagnosis without knowledge of basic facts. With the advent of fluorescent lighting, a wave of complaints arose and many users were convinced that the radiant energy from fluorescent lamps was particularly vicious in causing fading of dyed textiles. Those familiar with the spectral character of fluorescent light and its relationship to fading knew that the indictments were unjustifiable. What the user of fluorescent light neglected to take into account were the higher levels of illumination which commonly resulted from a change to fluorescent lighting. For example, the low-wattage tungsten-filament lamps in show-cases were replaced by fluorescent lamps emitting much more light. As a consequence, the edge of a necktie lying in a display case or the shoulder of a garment hanging in a wall-case close to the light-source received much more light than heretofore. Although the displays profited by more light of a better quality, the remedies lay in properly designing the lighting system, in changing the displays often enough, and in removing the materials to a safer distance so that no part of them was unduly exposed close to the light-sources.

These are glimpses of the everyday problems of fading and of the part played by light and lighting. With increasing use of ultraviolet energy, and particularly germicidal energy of $\lambda 2537$, the matter of fading and of its causes and prevention has become more important. As seen later, it is impossible to make an illuminant satisfactory for general use that will not cause fading of dyed textiles, wallpapers, etc., if the exposure is sufficient in intensity and time.

However, there is some consolation in the knowledge that for the same exposure such materials generally fade more under natural daylight. Therefore, materials which are reasonably fast under the usual intensities of natural light are generally adequately so under artificial light.

THE RECIPROCITY LAW

In an early research Luckiesh and Taylor [86] exposed a series of dyed ribbons to radiant energy from tungsten-filament lamps over a considerable range of intensities. Extensive data were obtained at levels of illumination of 50, 500 and 2700 footcandles. These cover a range of 1 to 54. They concluded that *on the average* the fading was approximately proportional to the product of intensity of illumination and the duration of exposure. This product is expressed in footcandle-hours. In other words, $Et = k$ where k in this case applies to this group of specimens. If every specimen faded in accordance with this law, there would be a specific value of k for each or, for a given degree of fading, there would be a specific value of Et.

Appel [87] tested seven dyeings which had shown unexpected results under daylight exposures and found that they did not obey the reciprocity law. Our studies of the effect of the spectral character of the illuminant have indicated that, when measuring exposure in terms of footcandle-hours, a higher rate of fading is to be expected with natural daylight than with fluorescent or filament light. Apparently the reason for this difference is the greater amount of long-wave ultraviolet energy associated with each footcandle of daylight than with either of the two artificial illuminants. It is conceivable that some dyeings will fade more when exposed for a long time under a low level of illumination than when exposed under a higher level of illumination for an equal number of footcandle-hours.

Regardless of exceptions, a generalization is so useful that even an approximate one is valuable for a practical consideration of the problems of fading due to light and radiant energy. We know that the reciprocity law not uncommonly breaks down at the extremes. Doubtless this relationship of exposure and fading also similarly fails. However, over considerable ranges the reciprocity law appears to hold well enough on the average to guide practice and practical considerations.

RESULTS WITH COMMON ILLUMINANTS

The advent of fluorescent lamps has created interest in the question of their effect upon the fading of dyed textiles and other materials whose colors were known to be more or less fugitive. Therefore, extensive tests were made with three illuminants whose spectral distributions of energy are indicated by A, B and C in Fig. 98. Exposure of the dyed textiles to natural daylight was made in a frame facing south and inclined at 45 degrees. This frame was covered with plate glass ⅛ of an inch in thickness. There was a space of 2 inches between the glass and the specimens. Incidentally, it has been shown that for the same intensity of energy on the specimens they generally fade the same whether covered with glass or not.

The exposures to natural daylight were made on sunny days in June and July between 9:00 A.M. and 3:30 P.M. At the center of the frame and in the plane of the specimens a photocell was placed behind a diffusing glass and a special filter, and was connected to an electronic integrator described elsewhere. The natural daylight varied both in intensity and spectral character. The former was integrated in terms of footcandle-hours. The mean color-temperature was about 6000° K. and the mean spectral distribution is represented by B in Fig. 98. The color-

temperature of the fluorescent light was 6500° K. and the spectral distribution of energy is represented by *C* in Fig. 98. The color-temperature of the tungsten-filament

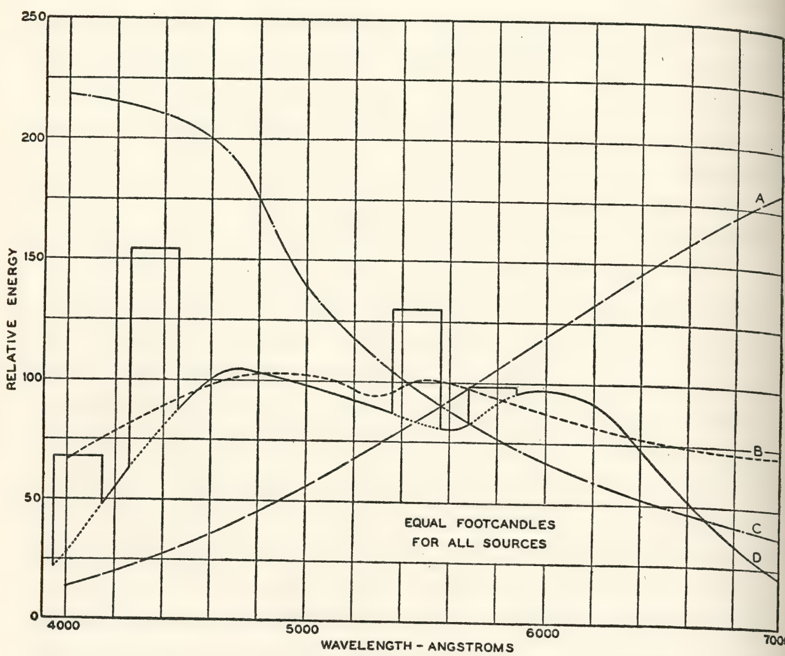


FIG. 98. The spectral distributions of energy in common illuminants for equal footcandles, *A*, tungsten filament 2850° K.; *B*, natural sunlight plus skylight 6000° K.; *C*, zenith blue sky 60000° K.; *D*, daylight fluorescent lamp 6500° K.

light, which was obtained from 50- and 75-watt lamps, was 2850° K. and its spectral distribution of energy is represented by *A* in Fig. 98. The fourth curve *D* in Fig. 98 indicates the spectral distribution of light from a blue sky on a very clear day. Skylight varies greatly in spectral character. Taylor and Kerr [88] have measured color-temperatures of skylight as high as 60,000° K.

The fading tests involved 120 different colors of dyed textiles. Of these 67 were obtained from the Sub-Committee on Light Fastness of the American Association of Textile Chemists and Colorists through the courtesy of W. D. Appel and W. E. Cady.[89] The materials of the 67 dyed specimens were as follows: 16 silk; 19 cotton; 16 wool; 8 viscose; and 8 acetate. To these we added 53 specimens of satin ribbons of assorted colors purchased in stores. Therefore, the 120 specimens were sufficiently representative for the practical purposes of the investigations.

Three complete sets of specimens were made so that one could be exposed under each illuminant. Details of the technique are available elsewhere.[90] It is sufficient to state that a sharp boundary line between the faded and unfaded portions facilitates detection and appraisal of fading. All specimens were examined and compared at frequent intervals. The best illuminant for the detection of the small color-differences between unfaded and slightly faded areas of the same specimen is generally one which is relatively rich in the spectral region of maximal absorption by the specimen. For example, slight degrees of fading of blue materials are more easily detected when viewed in the light from tungsten-filament lamps than when viewed in natural daylight or in the light from fluorescent daylight lamps. Conversely, small amounts of fading of red, pink and yellow materials are more easily detected under natural or artificial daylight.

Twelve of the 120 specimens did not fade sufficiently for appraisal during the period they were exposed. The relative exposures for equal fading, on the basis of 1.0 for natural daylight, are presented in Table XXXVII. It is seen that about three-fourths of the samples faded more rapidly under natural daylight than under the artificial illuminants

for the same exposure, *Et*. The average relative exposures for equal fading under the three illuminants are

1.00 for natural daylight, 6000° K.
1.81 for tungsten-filament, 2850° K.
1.68 for fluorescent daylight lamps, 6500° K.

Although fastness of a colored material is a relative matter, it is important to know how soon undesirable fading will occur under a given level of illumination in homes, stores, show-windows, display-cases and elsewhere. In the tests with 120 fairly representative specimens of dyed textiles, 50 percent of them were faded perceptibly by exposures of 50,000 footcandle-hours to either filament or fluorescent light. This exposure is equivalent to 100 footcandles for 500 hours or 2 months of 8-hour daily exposures. Of the 50 percent which faded perceptibly during a continuous exposure of 50,000 footcandle-hours, about half of these specimens were only very slightly faded. Therefore, only 25 percent of the 120 specimens were appre-

TABLE XXXVII

Distribution of 108 Colored Textiles with Respect to Exposure-Ratios (Footcandle-Hours) Required to Produce Equal Amounts of Fading with Three Light-Sources

Exposure Relative to Natural Daylight	*Number of Specimens Equally Faded under Tungsten Lamps*	*Fluorescent Lamps*
Below 0.5	4	4
0.51 to 0.75	12	9
0.76 to 1.00	12	12
1.01 to 1.25	10	14
1.26 to 1.50	15	13
1.51 to 1.75	14	17
1.76 to 2.00	8	10
2.01 to 2.25	14	14
2.26 to 2.50	2	1
2.51 to 3.00	2	3
3 to 4	9	6
Greater than 4	6	5
	108	108

ciably faded by an exposure of 50,000 footcandle-hours. This appears to be a value worth remembering in lighting practice involving colored textiles and other materials whose colors are likely to fade.

An analysis of fading data reported by Cady and Appel [89] for 1252 specimens of dyed textiles reveals that over 50 percent of them showed perceptible fading after an exposure to sunlight and skylight for 24 hours. Data on intensity of illumination are not available, but if it averaged 4000 footcandles, this exposure would equal 96,000 footcandle-hours. Considering that in the tests by Luckiesh and Taylor [86] only 25 percent of the specimens were faded appreciably by an exposure of 50,000 footcandle-hours to the artificial illuminants, the agreement may be considered satisfactory. In making this comparison the greater average fading power of natural daylight must also be taken into account. From the data on the 120 specimens, the relative fading power of the three illuminants would be

1.00 for natural daylight, 6000° K.
0.55 for tungsten-filament lamps, 2850° K.
0.60 for fluorescent daylight lamps, 6500° K.

Assuming that the exponential relationship holds in general over the common range of footcandle-levels and that 50,000 footcandle-hours is *on the average* a safe exposure to tungsten-filament light, we have

$$Et = 0.55 \times 55{,}000 = 30{,}250 \text{ footcandle-hours}$$

as a safe exposure to natural daylight for nearly all dyed textiles. For example, if the average level of illumination in a show-window is 275 footcandles, the safe duration of exposure is 100 hours. Assuming the daily exposure is 12 hours, the safe duration of exposure is 8.5 days, or about one week. These values are conservative for most dyed

materials but they illustrate the principle involved in safeguarding most of the fugitive colors.

In Fig. 98 the spectral distribution of energy in skylight on a typical clear day indicates relatively large amounts of energy in the short-wave visible and long-wave ultraviolet regions of the spectrum. Experimental evidence having directed suspicion to radiant energy in the region from λ3500 to λ4500, skylight was suspected of greater fading power than sunlight or artificial light. Therefore, 25 dyed ribbons were selected from previous tests as being sufficiently representative for this test. Each specimen was placed in a thin glass tube open at each end. One set was exposed at an open window to direct sunlight and some skylight from 8:30 A.M. to 5:00 P.M. on sunny days. The average intensity of illumination was 3900 footcandles. Another set was exposed to skylight outside a window with approximately northern exposure to an average intensity of 450 footcandles. The average results indicated that for equal fading the relative exposures are

1.00 for sunlight plus skylight
0.44 for skylight alone.

There appears to be little doubt that for equal levels of illumination the fading power of skylight is more than twice that of direct sunlight and is at least 3 times that of ordinary artificial illuminants.

Applications of the foregoing data are many, varied and easy. First it is necessary to agree on the relative fading power of the illuminants as determined by the average, or by most, of the specimens of a large number of dyed textiles. As previously explained, these materials are used not only for themselves but also as being generally representative of the more fugitive of the colored materials in use.

Suppose we round out the values previously determined and agree that the relative fading powers are

1.00 for natural sunlight
2.00 for natural skylight
0.60 for ordinary artificial light from fluorescent and filament lamps.

Now let us assume a show-window facing south with an average of 3000 footcandles of sunlight for 5 hours daily, 300 footcandles of skylight alone for 10 hours daily, and 100 footcandles of artificial light for 8 hours daily. The daily exposures in footcandle-hours weighted by the fading powers are

$$3{,}000 \times 5 \times 1.00 = 15{,}000$$
$$300 \times 10 \times 2.00 = 6{,}000$$
$$100 \times 8 \times 0.60 = 480.$$

The total exposure is 21,480 footcandle-hours and in any given period the percentage of the total fading contributed by each of the three illuminants is 70 percent for sunlight, 28 percent for skylight and 2 percent for artificial light.

Let us assume a show-window of northern exposure which receives an average of 300 footcandles of skylight for 10 hours daily and 100 footcandles of artificial light for 10 hours daily. The weighted footcandle-hours and the percentages which each illuminant contributes to the total fading are

$$300 \times 10 \times 2.00 = 6000 \text{ or } 91 \text{ percent}$$
$$100 \times 10 \times 0.60 = 600 \text{ or } 9 \text{ percent.}$$

It is a difficult matter to make out a case against ordinary artificial light when properly used. If a necktie or dress fades perceptibly in a week of exposure to 200 footcandles of artificial light totaling 100 hours on the average, it should fade as much in 10 minutes outdoors at noon on a clear summer day. Such fugitive materials should not be made and sold—and fortunately they seldom are.

Admittedly the footcandle-hour is not a complete measure of exposure for fundamental purposes. However, it is adequate when dealing with fading due to common artificial illuminants. Assuming the reciprocity law to hold, the final question to answer is, What is a safe average exposure in footcandle-hours? The answer rests upon another question, How much fading *on the average* will one accept? Preceding discussions provide the data for dyed textiles upon which anyone can decide for himself. Possibly a total exposure of 50,000 footcandle-hours is safe on the average for artificial light.

EFFECT OF SPECTRAL CHARACTER OF ILLUMINANT

There is a well-established fundamental principle known as the Grotthus-Draper Law. It states in effect that radiant energy must be absorbed in order to produce a photochemical effect. However, this law is commonly misinterpreted. Radiant energy of certain wavelengths may be absorbed, but may expend itself in heating the material. The absorption spectrum of the material only indicates the region or regions of the spectrum in which the wavelengths of the energy which cause the fading are to be found. It is analogous to determining the woods in which an enemy is hiding but not the tree or bush which conceals him. Therefore, absorption spectra of colored materials do not accurately predict the spectral energy which causes fading in any given case. This can be ascertained by independent exposures to energy in various parts of the spectrum.

There is some evidence that the fading power of the ultraviolet and blue regions of sunlight and skylight is relatively greater than that of energy in the remaining portion of the visible spectrum. However, the ultraviolet energy in daylight, which is highly absorbed by ordinary glass, is not responsible for an appreciable part of the fading

power of sunlight. The absorption spectrum of ordinary glass in the ultraviolet region begins at about λ3500 and the absorption increases rapidly to about λ3000 where it is nearly complete. Tests by the author and his colleagues [86] revealed little or no effect of ordinary glass when testing the fastness of dyed materials under natural or artificial light. Of 1252 specimens tested at the Bureau of Standards [89] under natural daylight outdoors the results of the presence or absence of window glass showed practically no difference on 74 percent of the specimens, only a slight difference on 22 percent, and a marked difference on only the remaining 4 percent.

These results do not mean that energy in the region of λ3000 to λ3500 does not possess significant fading power. Actually it means that the energy in that region is not as effective quantitatively as compared with the energy in the other parts of the spectrum of sunlight or skylight. This fact is indicated in Fig. 98 and in Chapter II.

In the comparative fading tests [86] with 120 carefully selected specimens of dyed textiles, there appeared to be a correlation between the color of the specimen and the relative fading under tungsten-filament lamps and fluorescent daylight lamps. For example, blue specimens appeared to fade somewhat more rapidly under tungsten-filament light, but red, pink and yellow specimens faded slightly more rapidly under the fluorescent light. However, for most of the specimens the difference in the rate of fading was not great and the average rate for all the specimens was almost exactly the same.

Tests with selected specimens of assorted colors were made under 9 different filters with short-wave cut-offs ranging from about λ2900 to about λ5700 and did not reveal any spectral region as being outstanding in fading power. The results indicate that radiant energy of wave-

lengths longer than λ6000 is relatively ineffective in fading of many specimens. This conclusion was further confirmed by covering dyed textiles with red, green and blue glass filters while exposing them to sunlight. The greatest amount of fading occurred under the blue glass, less under the green and very little under the red. In making the appraisals the different intensities of sunlight on the three sets of specimens were properly taken into account by determining the exposure under each filter which produced equal fading.

Some specimens were exposed to a sodium lamp which radiates relatively little ultraviolet energy and practically no visible energy excepting in the region of λ5890. The results indicated that the fading power of visible energy in the orange-red region of the spectrum is relatively low. The same specimens faded 5 to 85 times more rapidly under a modern germicidal source which radiates nearly all of its ultraviolet energy in the region of λ2537 and which radiates comparatively small amounts of visible energy.

COLOR CHANGES DUE TO FADING

For many of the specimens, spectral reflectance curves were made both for the unexposed and exposed materials. Typical curves are shown in Figs. 99 and 100 where *N* and *F*, respectively, indicate the unfaded and faded specimens. For nearly every specimen examined in this manner it was found that the material bleaches (reflectance increases) in the spectral region of maximum absorption, and darkens (reflectance decreases) in the region of minimum absorption. The resultant effect may be to make a faded material appear either lighter or darker depending upon the spectral character of the original color of the material. For example, several green specimens became darker when faded since

the spectral region of minimum absorption is near the middle of the visible spectrum where the energy is of maximal luminosity. Conversely, purple specimens commonly became lighter when faded, as is somewhat indicated by the pink specimen illustrated in Fig. 99. Blue

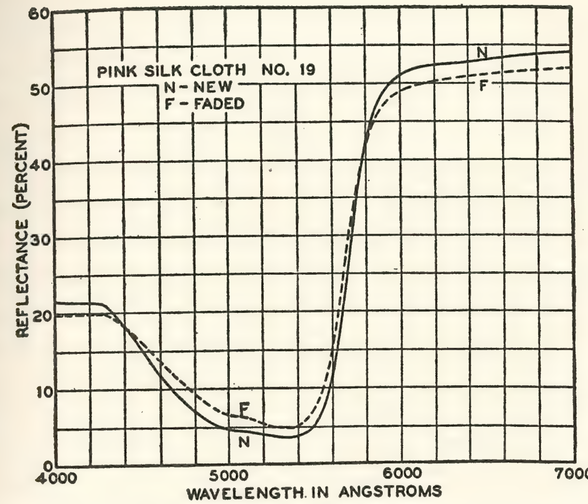


Fig. 99. Spectral reflectance of a specimen of pink silk before *N* and after *F* moderate fading.

specimens usually become lighter when faded. Conversely, yellow or orange specimens usually become darker as indicated in Fig. 100. These facts also give an idea of the value of different illuminants in detecting and appraising fading.

EFFECT OF GERMICIDAL ENERGY OF λ2537

The new efficient germicidal sources are likely to be extensively applied under conditions which are bound to affect some materials. The energy of λ2537 not only kills living organisms but is rather vicious in other ways. It

affects many materials and can cause undesirable fading. On the other hand, it might possibly serve as a means for accelerating fading tests. There is no rational basis for comparing fading under two different sources of radiant energy. However, it is of interest to compare the fading

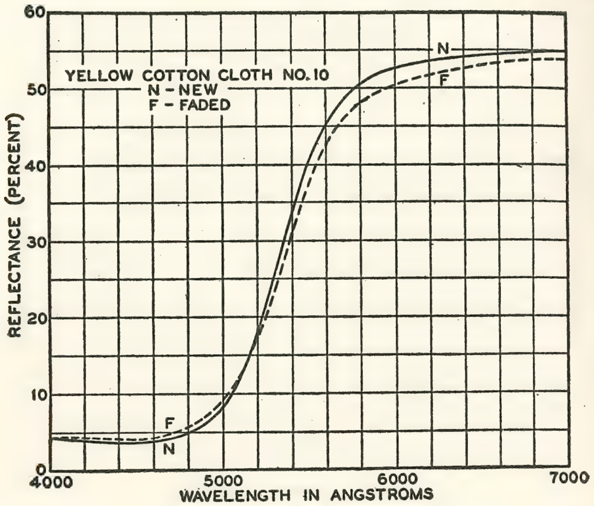


Fig. 100. Spectral reflectance of a specimen of yellow cotton cloth before *N* and after *F* moderate fading.

power of this germicidal energy with that of an artificial illuminant. Through the courtesy of Appel and Cady,[91] duplicates of their 40 selected dyed textiles were obtained. These varied in color throughout a wide range and included cotton, wool, silk and rayon textiles.

A portion of each specimen was exposed 26 inches below a bare 30-watt germicidal source. The intensity of germicidal energy of λ2537 on the specimens varied from 68 at the ends to 90 microwatts per sq. cm. in the middle of the set of specimens. This condition may readily obtain in germicidal installations. A. H. Taylor,[92] who conducted

this investigation, inspected the materials at frequent intervals. Whenever a specimen had faded perceptibly, it was covered with black paper and the duration of exposure in hours was noted. Exposure of the other specimens continued. At the end of 420 hours, exposure to germicidal energy ceased.

The exposed areas were covered and new areas were exposed 10 inches below two 30-watt fluorescent daylight lamps in aluminum reflectors. The initial intensity of illumination was 200 footcandles at the ends of the set and 300 footcandles in the middle. Inspections were made at frequent intervals and whenever a specimen had faded as much under the fluorescent light as it had under germicidal energy, it was covered with black paper and the duration of exposure in hours was noted. Exposure to fluorescent light ceased at the end of 3850 hours.

All but one specimen required much longer exposures to the fluorescent light than to the germicidal energy for equal fading. Eleven of the specimens were far from equally faded under fluorescent light at the end of 3850 hours. The exposures resulting in equal fading for each of 29 specimens are plotted in Fig. 101. The degree of fading was not necessarily the same for any two of these specimens. The two dots on the upper left-hand corner indicate that these two specimens faded as much in 110 hours under the germicidal energy as they did in 3850 hours under 200 to 300 footcandles of fluorescent light. This is a ratio of 1 to 35 in exposure. In many cases this ratio was more than 1 to 10. The lowest ratio is about 1 to 2.

These results emphasize the need for care in installing germicidal sources where fading of textiles, wallpaper, etc., would be undesirable. In addition, the results indicate the possibility of using germicidal energy for accelerated tests of light-fastness. Since energy of λ2537 is not present in

sunlight, the results are not directly comparable. However, fastness to energy of λ2537 would generally guarantee fastness to natural or artificial light.

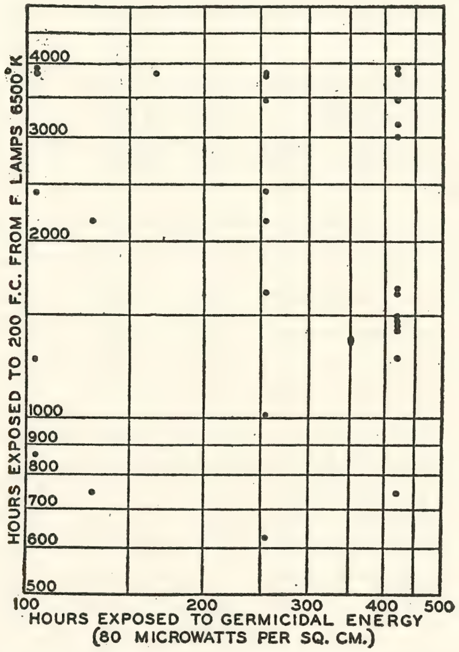


FIG. 101. Comparative duration of exposure for equal fading under 200 footcandles from fluorescent daylight lamps and 60 microwatts per sq. cm. of germicidal energy of λ2537.

Plastics are rapidly coming into use in lighting equipment. When too close to a tungsten-filament lamp, they may become discolored, like a scorched white fabric, if the temperature is too high. Colorless plastics appear to be reasonably permanent in appearance, even those that are exposed to intensities of light from fluorescent lamps for long periods. However, some do not fare so well under long exposures to germicidal energy. For example, a white

diffusing plastic which is used in fluorescent fixtures, exposed for 12 days to an intensity of 135 microwatts per sq. cm. of germicidal energy (λ2537), had become decidedly gray. Another piece of the same plastic was similarly exposed to the germicidal energy, but in addition was simultaneously exposed to an intensity of 750 footcandles from fluorescent daylight lamps. After 12 days it had changed to the same gray that resulted from exposure only to germicidal energy. In other words, the 750 footcandles of fluorescent light had no effect. Specimens of white plastics placed about two inches from the tube of a 30-watt germicidal source turned to a decidedly brown color in a week. At this distance the plastics are no more than mildly warm, but it is likely that the higher temperature while the germicidal energy was acting possibly accounted for the brown instead of the gray color.

These are mere glimpses of the powerful action of germicidal energy of λ2537. Such effects must be avoided in the use of these germicidal sources for disinfecting air. On the other hand, this undesirable property of germicidal energy may find some uses. The effect on plastics and most materials is generally purely superficial for the reason that it is absorbed by most materials and, therefore, its effects are produced in a thin surface layer.

ACCELERATED FADING

Those interested in the fastness of dyes and other colored media and in the permanency of other materials have long recognized the need for an artificial source of energy for testing purposes. No single source has as yet been developed which duplicates the spectral distribution of sunlight or skylight or any combination of them throughout the entire spectrum. Certain carbon-arcs have long been used with success. It now appears that a bank

of fluorescent daylight lamps would be practicable. If accelerated tests are desired, perhaps the germicidal sources used alone or in combination with fluorescent lamps might be satisfactory. However, it is obviously necessary to establish at least approximate correlations between such accelerated tests and actual tests under natural daylight.

In Chapter X various aspects of artificial sunlight are discussed along with the spectral distribution of energy from artificial sources. The water-cooled AH-6 mercury lamp has possibilities for accelerated testing. Very high intensities of energy are obtainable without undue heating effect. If a quartz flow-tube is used, a good deal of ultraviolet energy shorter than λ2900 would be available. This energy could be used when desired and filtered out at will with various glasses. Where carefully controlled accelerated tests are important, this powerful source may also be worth considering.

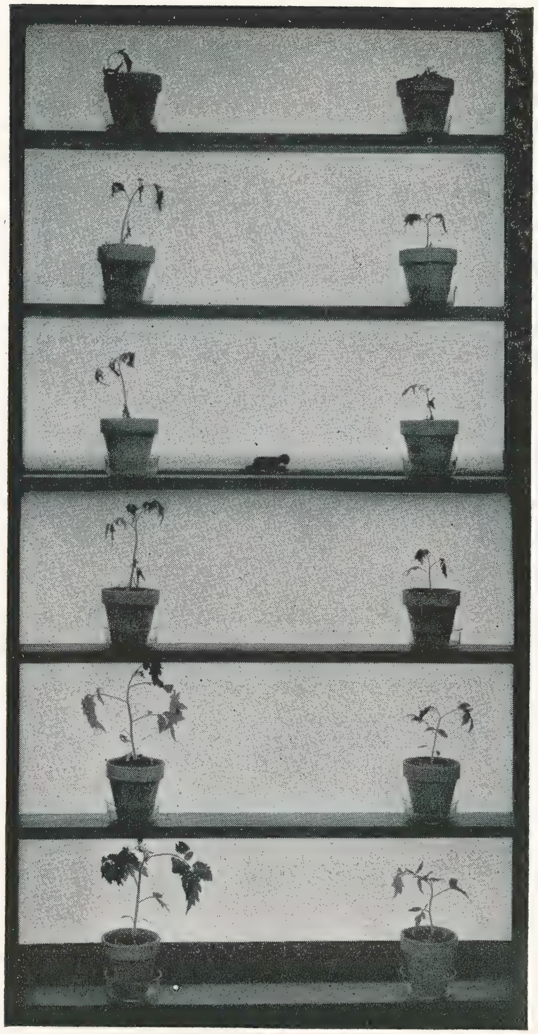


PLATE XII. Young tomato plants resting on shelves in a window and exposed continuously to germicidal energy (λ2537) varying from 1.9 microwatts per sq. cm. at the plants on the top shelf to 0.14 microwatt per sq. cm. on the bottom shelf. Plants on the top shelf died after an exposure of only 24 hours. Those on the bottom shelf showed only slight damage after 500 hours.

Ultraviolet Energy and Plant Life

THE EFFECTS of ultraviolet energy upon seeds, seedlings and mature plants have been studied from various viewpoints in many researches. Some of the disagreement and uncertainty is due to the complexity of the problems involved. Plants almost universally require light or visible radiant energy. This is accompanied by ultraviolet and infrared energy. Therefore, these factors must be taken into account in dealing both with test and control specimens. This involves measurements that many investigators have not been able to make. The result is an absence of adequate data pertaining to the intensity and spectral character of the radiant energy used. In other words, the radiant energy is not adequately described, and much of the published work is of no quantitative value and of doubtful qualitative value. This is too often true in therapy and in other fields in which radiant energy is the important agency.

A good deal of attention has been given to the short-wave radiant energy in daylight, particularly in the region of λ2900 to λ3200, which is generally absorbed by ordinary window glass of the usual thickness. However, when the results of the investigations are examined in detail and viewed collectively, the conclusion is that this ultraviolet energy is generally of little or no influence upon the germination of seeds, the growth of seedlings and the maturity of plants. There are some indications that this short-wave ultraviolet energy may have some influence at high altitudes where it is more abundant due to less atmospheric absorption. But the other factors in the environment are

also different than at lower altitudes so that no clear-cut proof has been forthcoming as yet.

Underlying this entire matter of radiant energy and its influence upon plant life is the outstanding fact that sunlight and skylight have been powerful environmental factors under which plants in general have evolved. Therefore, it appears unlikely that, in general, there is something missing from, or harmful in, natural daylight. Of course, if the natural habitat of a plant is changed, artificial radiant energy of certain wavelengths might be beneficial or detrimental. However, it is not surprising that no startling results have been obtained with normal intensities of ultraviolet energy in the region of λ2900 to λ3200. Those who are interested in the many investigations involving radiant energy will find that an excellent summary of its biological effects has been presented by Duggar.[3]

If one fully grasps the importance of natural daylight as an environmental factor during eons of adaptation and evolution of plant life, he can scarcely be surprised to find that ultraviolet energy shorter than λ2900, in sufficient dosages, is harmful to plant life. If one considers the increasing erythemal effectiveness upon human skin, as the wavelength decreases from λ2800 to λ2500, he will not be surprised to find a similar increasing effect on leaves of plants. In Fig. 102 the lethal effectiveness of energy of various wavelengths, as determined for the leaves of tomato plants, is plotted along with the spectral erythemal effectiveness on average untanned white skin. Doubtless it is more than a coincidence that the two curves are approximately the same for energy of wavelengths beyond the solar spectrum. There is no reason to expect that the destructive effect of radiant energy of various wavelengths should be markedly different for the superficial surface of tender leaves than for that of tender skin.

From the viewpoint of present knowledge, ultraviolet energy of wavelengths beyond the short-wave limit of the solar spectrum is at least a lethal agency. With the increasing use of germicidal energy of λ2537 in killing air-borne micro-organisms, it becomes of practical interest to know what dosages are lethal to plants and the relative resistivities

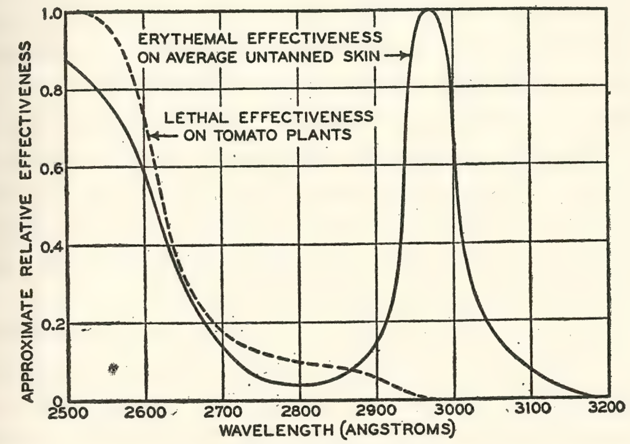


FIG. 102. Spectral lethal effectiveness of ultraviolet energy for leaves of tomato plants compared with spectral erythemal effectiveness for average untanned human skin.

of various species. At least some idea of the threshold dosage and of the range of susceptibility of plants is necessary in dealing with germicidal installations. Energy of λ2537 is rather vicious in its effects upon living matter. This is also a relatively new tool. Possibly it may eventually be useful in killing undesirable organisms responsible for plant diseases. One might also hope that it might kill weeds without killing the grass in lawns. Such applications will have to await the results of much more work.

In order to obtain some idea of the threshold dosages which are not harmful to plants and also some idea of the

variation in susceptibility of various species of plants, 2500 plants of 19 different species were exposed individually to measured intensities of germicidal energy of λ2537 for various periods of time. This energy is very readily absorbed by most substances and in general it is not likely to penetrate far into plant structures. Owing to the fact that it must penetrate somewhat in order to destroy living matter, it is to be expected that the resistivity of various species will differ considerably because of the different degrees of protection afforded by the superficial coverings of leaves and other portions of the plants. In fact, for the same reason it is to be expected that different areas of the same plant will vary in resistivity to this energy. In other words, waxy coatings of leaves and fibrous surfaces of other parts should offer protection against a given dosage which might be lethal to thin tender leaves.

The results of testing quite a number of individual plants of 19 different species indicate a range of resistivity or susceptibility of at least 1 to 50. This is about the range indicated for micro-organisms ranging from bacteria through fungi, spores, yeast cells, etc. In all tests 30-watt germicidal sources were used and measurements of energy were made by means of devices developed in the course of more than three decades of research by the author and his colleagues.

All the plants that were tested were raised from seed indoors. There is some indication from relatively meager experiments conducted outdoors on lawn grasses and weeds that these are less susceptible in general than the same plants grown from seed indoors. Insufficient data were obtained for the outdoor plants to be certain of such a conclusion, but it would not be surprising if this were found to be true. It also appeared that when the plants were growing in a window which received abundant sunlight, they were

somewhat more resistant than when growing in a window which received much less light from a patch of sky.

GERMICIDAL ENERGY AND TOMATO PLANTS

Among the different species exposed individually to known intensities of germicidal energy for various periods of time, tomato plants were the most susceptible to energy of λ2537. Therefore, several hundred tomato plants were exposed individually to intensities of germicidal energy varying from 0 to 50 microwatts per sq. cm. for periods of time varying from 0 to 500 hours. A good deal of attention was concentrated on intensities varying from 0 to 2 microwatts per sq. cm. In using germicidal energy for disinfecting the upper strata of air in rooms, a slight amount is reflected to the lower occupied area. From the available knowledge, it has been concluded that a fraction of a microwatt per sq. cm. impinging upon the skin or eyes for long periods is permissible.

Tentatively, a permissible value of 0.5 microwatt per sq. cm. has been established for continuous 8-hour exposures of human occupants. For continuous 24-hour exposures of infants in hospitals, the tentative permissible value is 0.1 microwatt per sq. cm. The permissible exposure or dosage for 8-hour occupancy is 240 microwatt-minutes per sq. cm. This is less than an equivalent MPE dosage in 8 hours.

It appeared sufficient for the primary purpose of the investigation to note the appearance of the leaves and to describe the degree of injury. Naturally, plants of the same species raised under the same conditions differ somewhat. The measurements of germicidal energy were made at the plants, but the different orientations of the leaves varied the intensity at their surfaces. These variations, combined with the criterion of appearance of observable damage, do not conspire for high accuracy. However, by testing many

plants individually, a fairly dependable dividing line between slight damage and severe injury, from which the plant cannot recuperate, can be established.

In Table XXXVIII typical results are presented for continuous exposure to the intensities of germicidal energy

TABLE XXXVIII

Effects of Germicidal Energy of λ2537 on Typical Tomato Plants Exposed Continuously to Different Intensities for Different Periods of Time

Microwatts per Sq. Cm.	*Hours Exposed*	*Microwatt-Minutes per Sq. Cm.*	*Injury to Leaves*
0.27	87	1410	severe
.30	69	1240	slight
.34	69	1370	severe
.53	69	2200	severe
.53	69	2200	severe
1.6	11	1080	slight
3.6	5	1080	slight
4.4	4	1080	severe
6.7	3	1080	severe
12	1.3	960	slight
12	2	840	slight
18	1	800	slight
44	.3	880	slight
500	1.7	875	slight

indicated. These data were chosen as representative of several hundred tomato plants that were individually exposed and observed. They show typical variations in the results of exposure of various plants. It required about 15 hours for the injury to develop fully after it had been inflicted. Therefore, examinations for injury were commonly made the day after exposure. The plants exposed continuously to very low intensities were examined daily.

From the large number of tomato plants exposed to intensities of energy of λ2537, varying from 0.27 to 44 microwatts per sq. cm. for continuous periods varying from 87 hours to 20 minutes, it appears that an exposure of

800 or 900 microwatt-minutes per sq. cm. causes a slight but definite injury to the leaves. Exposures not much greater than 1000 microwatt-minutes per sq. cm. caused such severe injury to the leaves that the plants usually died.

Fig. 103. The upper group illustrates the effect upon young tomato plants of a total exposure of 1080 microwatt-minutes per sq. cm. of energy of λ2537. The left-hand control plant received none of this energy. With the exception of left-hand plant, the lower group received dosages greater than 1240 microwatt-minutes per sq. cm.

In Fig. 103 are illustrated typical results with two groups of young tomato plants. The upper group was exposed continuously to germicidal energy for a total dosage of 1080 microwatt-minutes per sq. cm. All the plants received abundant daylight in a window and were treated the same excepting for exposure to germicidal energy. The plant on the extreme left received no energy of λ2537. The other plants from left to right were exposed from one side

to intensities of germicidal energy of 6.75, 4.43, 3.6, 1.64, and 1.6 microwatts per sq. cm. The corresponding periods of exposure to these intensities were 160, 243, 300, 660, and 675 minutes. At the end of the periods the injuries to the plants may be described, from left to right, as none, severe, severe, slight, slight, very slight. It will be noted that for the lower intensities of energy of λ2537, the same total dosage produced less injury than for the higher intensities. A good deal of evidence of this sort appears to indicate that the reciprocity law begins to break down at these low intensities for young tomato plants.

In the lower group of Fig. 103 the young tomato plants, excepting the control plant at the left-hand end, were exposed from one side to intensities varying from 0.27 to 0.53 microwatt per sq. cm. for various periods of time. All the exposures were greater than 1240 microwatt-minutes per sq. cm. and all the plants were severely damaged.

A continuous exposure to 0.1 microwatt per sq. cm. commonly produced a slight injury which generally did not kill the young tomato plants. At any rate those that were exposed continuously to this intensity for 500 hours were only slightly damaged, and they continued to grow when located in a window receiving abundant daylight. This exposure totals 4200 microwatt-minutes per sq. cm. Apparently at this relatively low intensity the reciprocity law breaks down. At higher intensities of germicidal energy, slight injury was commonly produced by 900 microwatt-minutes per sq. cm.

It is seen that a young tomato plant grown indoors from seed is a rough indicator of the permissible intensity to which human occupants of a room may be exposed for long periods. It will be recalled that 0.5 and 0.1 microwatt per sq. cm. have been tentatively established as permissible intensities, respectively, for 8-hour and 24-hour continuous exposures of human beings in rooms in which the upper strata of air are being disinfected with germicidal energy. If young tomato plants are located in the region occupied by human beings and they are not injured, apparently human eyes and skin will not be noticeably affected.

In Plate XII is illustrated the effect upon young tomato plants exposed continuously to different low intensities of germicidal energy of λ2537. The shelves were built in a window exposed to abundant daylight. The lowest shelf was 3 feet above the floor and the highest shelf was 8 feet above the floor. A 30-watt germicidal source was located on the other side of the room 7 feet above the floor. It was installed in a germicidal fixture which emitted no energy below the horizontal plane. The intensities of germicidal energy ranged from 1.9 microwatts per sq. cm. on the highest shelf, on which the young tomato plants were located, to 0.14 microwatt per sq. cm. on the lowest shelf. All the tomato plants were originally of the same age and size. They received the same amount of daylight and the same treatment in every way excepting for the different intensities of germicidal energy to which they were continuously exposed.

The photograph reproduced in Plate XII was made at a time when the tomato plants on the highest shelf were practically dead from 24 hours of exposure to 1.9 microwatts per sq. cm. The plants on the lowest shelf were only slightly damaged after 500 hours' exposure to 0.14 microwatt per sq. cm. Slight injury of the plants on the other shelves occurred after 38, 49, 66 and 140 hours of continuous exposure to intensities, respectively, of 0.67, 0.44, 0.31 and 0.19 microwatt per sq. cm. Similar shelves were installed in a window of the same exposure in an adjacent room. These control plants developed equally and normally on all the shelves.

The effect of intermittent exposures was studied by daily dosages. Young tomato plants exposed 3 minutes daily for 21 days to an intensity of 50 microwatts per sq. cm. of energy of λ2537 were only slightly damaged. The total dosage was 3000 microwatt-minutes per sq. cm. Those exposed 4 minutes daily to the same intensity for 21 days were severely damaged by the total dosage of 4000 microwatt-minutes per sq. cm. If enough plants are tested, a rather sharply defined boundary becomes apparent between exposures that are fatal and those from which young tomato plants can recuperate.

Daily 8-hour exposures of tomato plants to 0.53 microwatt per sq. cm. on 4 successive days caused definite injury. The total dosage was 1020 microwatt-minutes per sq. cm. Apparently, 8-hour daily exposures are about as harmful as equivalent continuous exposures. This is not true of brief daily exposures from which the plants have time to recuperate during the long intermissions.

EFFECT ON VARIOUS SPECIES OF PLANTS

Besides the large number of tomato plants, 18 other species were exposed to germicidal energy. The number of individual plants of these species varied considerably but was generally adequate for the immediate purpose of the investigation. Most of the plants were young and were grown from seed. The exceptions are the coleus, chickweed, sedum, dandelion and parsley. These were fairly mature plants.

In Table XXXIX are the average results obtained with the various species. The average intensity of energy of λ2537 is indicated in each case. In the last column is the approximate dosage or exposure which caused a slight observable damage. The maximum dosage from which the plants could recuperate from the injury caused is appar-

ently about twice that which caused a slight observable damage. This appeared to be approximately true for all the species excepting the tomato plants and possibly the coleus slips and leaves. With these the differential appeared to be

TABLE XXXIX

Approximate Exposures to Energy of λ2537 Which Resulted in a Slight Damage to Growing Plants of Various Species

Species	*Microwatts per Sq. Cm.*	*Microwatt-Minutes per Sq. Cm.*
Tomato	44	880
Coleus slips	150	900
Coleus leaves	200	4,300
Lettuce	150	1,200
Beans, bush	250	2,500
Chickweed, common	250	7,500
Marigold	250	8,000
Calendula	300	9,000
African daisy	400	10,000
Sedum acre	400	10,000
Yarrow	400	12,000
Timothy	250	15,000
Dandelions	300	19,000
Creeping bent	170	20,000
Pepper	250	20,000
Parsnips	350	21,000
Chickweed, Mouse-ear	190	22,000
Mint	300	22,000
Parsley	400	24,000
Chives	250	45,000

much smaller as seen in the previous section for tomato plants.

From the evidence obtained with 2500 plants of 19 different species, it appears plants will not be damaged by the small permissible dosages or exposures of occupants of a room whose upper stratum of air is being disinfected by germicidal energy. In fact, it appears that most plants can withstand greater dosages than those to which human occupants should be subjected. Young tomato plants are rela-

tively much more susceptible to this energy than the other potted plants that were tested. It is possible that other species are quite as susceptible. In any case, care should be exercised where plants are involved, for probably there are few species that can withstand long exposures even to moderate intensities of germicidal energy. Apparently young tomato plants are conservative indicators of permissible intensities of germicidal energy to which human eyes and skin can be safely exposed.

The germicidal sources of energy of λ2537, which are being extensively used, may also be considered to be new tools by those interested in the biology of plants. It is quite probable that this efficient source of lethal energy will be used in many researches. It is easy to imagine that it may eventually find some special uses in destroying certain organisms detrimental to plants without damaging the plants. Radium and X-rays are serving in an analogous manner in destroying undesirable cells without destroying the normal ones.

THE EFFECT OF OZONE

Sources of germicidal energy produce more or less ozone. In fact, the designer of these sources is confronted with obtaining a high production of energy of λ2537 without transmitting too much ultraviolet energy of shorter wavelengths which produces ozone. The production of ozone and permissible concentrations of it in the air breathed by human occupants are discussed in Chapter VIII. Here we shall deal with the effect of ozone on plants. Primarily we are concerned with the effect of concentrations of ozone which are produced by germicidal installations in interiors that may be occupied by plants as well as by human beings.

Considerable work has been done with ozone in relation to its effects upon fruit in storage, upon certain spores, and various other aspects of plant life and growth. The results are somewhat conflicting, but there appears to be evidence [94] that peaches and bananas are injured by concentrations of ozone of the order of 200 parts per 100 million parts of air. It also appears that 4000 parts of ozone in 100 million of air may retard ripening. These glimpses are given merely for the sake of comparison with 10 parts of ozone in 100 million parts of air which has been tentatively established as permissible for breathing. Incidentally, it is seen in Chapter VIII that this low concentration of ozone is achievable with germicidal installations, the purpose of which is to disinfect air in the room. In general, any harmful effects of ozone in the vegetable kingdom are associated with relatively high concentrations of ozone which are many times greater than the 10 parts of ozone per 100 million which is a conservative value for breathing air.

In order to test the effect of ozone produced by germicidal lamps, 150 young growing plants of 10 species were installed on shelves in vertical northwesterly windows which received light from the entire quadrant of sky. These windows were in adjacent rooms and the environment and treatment of the plants were the same excepting for concentrations of ozone in the air. Plants grown from seeds were aster, lettuce, marigold, tomato, pepper, zinnia, petunia, red top and ageratum. Coleus slips were grown in a liquid solution of chemicals. All the other plants were young and were growing in pots.

The plants were divided into three identical groups of 50 each and one group was similarly placed on shelves in each of the large northwesterly windows in adjacent rooms. The upper part of each room was irradiated continuously with the energy from one 30-watt germicidal

source which was adequate for disinfecting the air. The rooms were 14 ft. by 17 ft., with a 12-foot ceiling. One room was used as a control with a normal concentration of ozone as produced by a regular 30-watt germicidal source.

To obtain a higher concentration in the second room, additional ozonized air was produced by a potent germicidal source and this was exhausted into the tightly closed room. This resulted in an intermediate concentration of ozone considerably higher than that desirable for breathing air.

In the third room, highly ozonized air was supplied to the plants in the window by sealing off the shelves from inside the room but leaving the plants fully exposed to the skylight as in the other two windows in the other two rooms. A very potent 30-watt germicidal source was enclosed in a box and it produced ozone at a much higher rate than the regular 30-watt germicidal sources. This air, with its high concentration of ozone, was blown at a rate of 40 cu. ft. per minute into the sealed space where the plants were located.

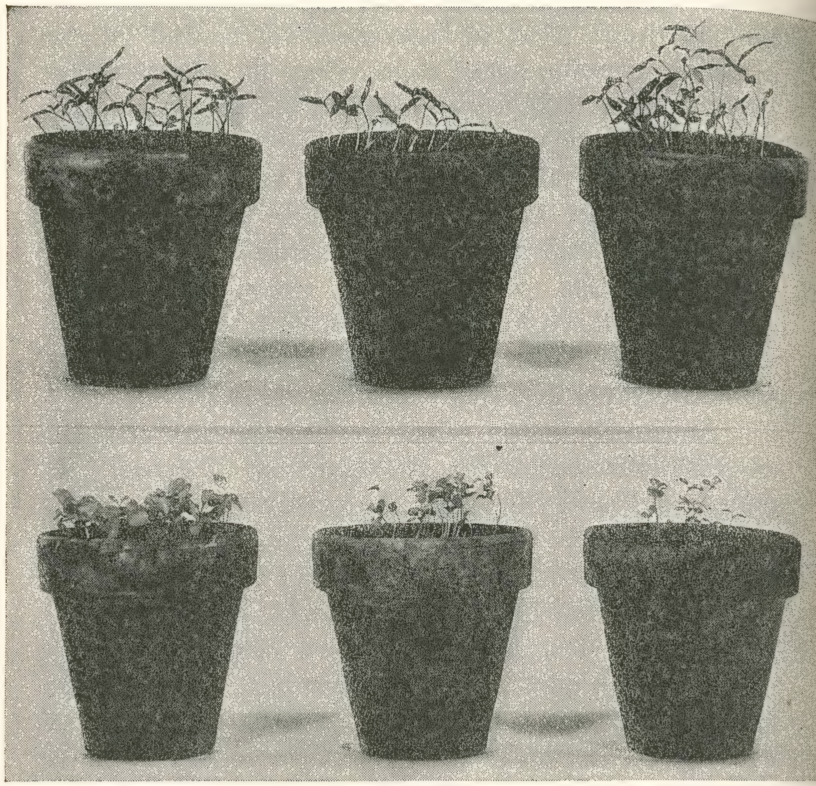
As a result of these conditions, identical sets of 50 plants of 10 species each were located in identical windows and each set received the same exposure and treatment excepting that the concentrations of ozone were normal, intermediate, and excessive. No accurate measurements of the concentrations were made for they were not necessary to the primary purpose of this investigation. In the second and third rooms the concentrations of ozone were much greater than occupants would be content to breathe continually.

Six species of seedlings and the coleus slips were exposed continuously for 14 days, and 9 species of transplants were exposed for 22 days. None of the plants, with the exception of tomato seedlings and transplants, appeared to be harmed by the normal and intermediate concentrations of ozone. Most of them were not harmed by the excessive concentration of ozone. Only the tomato plants appeared to be definitely damaged by the high concentration and probably by the intermediate concentration of ozone. Aster and marigold seedlings and transplanted pepper and zinnia plants actually appeared to be benefited by the highest concentration of ozone. No stress is laid upon the apparent benefits to some of the species. However, it appears that much greater concentrations of ozone than would be tolerated by human occupants did not harm any of the 10 species of plants which were tested.

Apparently tomato plants are among those that are adversely affected by high concentrations of ozone. The upper group in Fig. 104 illustrates tomato seedlings exposed from left to right, respectively, to excessive, intermediate and normal concentrations of ozone in terms of concentrations produced by germicidal installations in occupied interiors. The lower group illustrates marigold seedlings under the same conditions. There was little doubt that the appearance of the seedlings was definitely best after an exposure of 336 hours to an excessive concentration of ozone. How definite this benefit is can scarcely be answered by these limited tests.

This investigation should be viewed only as a reconnaissance, and about the only conclusion that is justifiable is that the concentrations of ozone produced by properly designed germicidal installations do not harm plants in general. There may be exceptions, but it is doubtful whether plants are harmed by 10 parts of ozone in 100 million parts of air. This is only about 10 times the average concentra-

tion of ozone outdoors and is about twice the value which has been measured on some days outdoors.



EXCESSIVE INTERMEDIATE NORMAL

FIG. 104. Illustrating the effect of ozone concentrations on the growth and appearance of tomato seedlings (upper row) and marigold seedlings (lower row). Excessive and intermediate concentrations affected tomato plants adversely. Excessive concentrations appear to benefit the marigold seedlings.

Whether the benefits to some plants of high concentrations of ozone is significant or important is incidental from the major viewpoint of this discussion. However, these new germicidal sources produce ozone without vitiat-

ing the air in other ways as electric arcs and discharges do. They can be made to produce ozone even far more rapidly than the regular sources do at the present time. Here again they are new tools which may intrigue plantologists and others interested in plant growth, storage of fruit and other phases of vegetable life.

Radiant Energy in Common Illuminants

THERE ARE various reasons for discussing and comparing natural and artificial illuminants. All living things on earth evolved under the radiant energy from the sun and sky outdoors, including human beings and their eyes and skin. Therefore, artificial illuminants are inevitably compared with natural daylight. To be safe, their short-wave spectral limit must not extend significantly beyond λ2900. To be suitable for general use, they must not depart too much in spectral distribution of energy from that of the extremes of sunlight or skylight. Also they must have a continuous spectrum to be satisfactory for color discrimination.

Natural and artificial illuminants in common use are of interest from the viewpoint of this book for the primary reason that light for seeing is accompanied by ultraviolet energy. Oddly enough, with few exceptions the ultraviolet energy which accompanies natural light is commonly applauded for its beneficial effects, but that present in common illuminants, when considered at all, is likely to be suspected of being harmful to the eyes and sometimes to the skin. This perversity is particularly interesting when one reflects that normal healthy human beings have suffered from severe "sunburn" and "snowblindness" from excessive exposure to the ultraviolet energy in natural daylight, but they have had no such experiences with common artificial illuminants in general use.

The author has long been concerned with limiting the spectral range of artificial light for general use to that of outdoor daylight and with keeping the intensity of biologically-effective ultraviolet energy, which accompanies

PLATE XIII. Spectral range of transmission of eye-media for energy emitted by iron arc. (After E. K. Martin)

A. Spectrum of iron arc, 2 sec.
B. Cornea, 5 sec.
C. Lens (thin section), 3 sec.
D. Lens (section 1/16 in. thick), 1 sec.
E. Lens (section 1/8 in. thick), 6 sec.
F. Lens (entire), 80 sec.
G. Vitreous humor (3/16 in.), 30 sec.
H. Vitreous humor (3/16 in.), 3 sec.

artificial light for seeing, well within the safe limits for eyes and skin. On the other hand, he has been interested for more than three decades in the possibility and practicability of providing the beneficial effects of natural daylight by means of common artificial illuminants while they are serving in their primary role of providing light for seeing.

If we accept this dual role of natural sunlight and skylight outdoors, there is no reason for not recognizing and accepting a similar role for an artificial illuminant. The problem merely resolves itself into developing an artificial illuminant that can qualify for the dual role. Until such an illuminant is available, the two roles may be played, respectively, by an illuminant suitable for seeing purposes and by another source of radiant energy which supplies the desirable biologically-effective ultraviolet energy.

In considering the harmful and beneficial effects of the component of ultraviolet energy in common illuminants, visible and infrared energy become involved. There are such matters as comparison of the spectral distributions of the visible energy in natural and artificial illuminants, of the intensities of illumination encountered or practicable, and of the desirable and undesirable contributions of infrared energy. Many misunderstandings, baseless theorizings and erroneous conclusions in regard to these various associated factors of common illuminants are born of a lack of quantitative measurements and failure to recognize certain established facts and principles. These can only be clarified by means of quantitative measurements combined with adequate knowledge of the complexities of biological and other effects of radiant energy, and of the involved facts and relationships of light, vision and seeing. These are not realms in which superficial knowledge and experience are dependable or in which conclusions can be safely formulated without quantitative measurements. Furthermore,

mere opinions have no more weight in these realms than they have elsewhere.

Here it is well to point out that spectrograms such as are illustrated in Plates I and III are commonly misinterpreted. At best they do not present quantitative values. To the expert they are valuable. Long exposure may record energy of certain wavelengths which is entirely negligible from a quantitative viewpoint. Over-exposure will also extend the spectrum beyond its significant limits when the energy is actually considered quantitatively.

The advent of a new source of artificial light commonly results in various suspicions and complaints. This is sometimes true in a lesser degree when a radical change in a lighting installation is made. Anyone who has witnessed various major advances in light-production, in level of illumination, and in systems of lighting, and who has been in a position to receive inquiries and complaints, knows that most of these are quite unwarranted on either a factual or a theoretical basis. Many appear to spring from a confusion of glare with a meager acquaintance with the known facts of radiant energy. Confusion of this sort can only be dissipated by quantitative measurements and experienced observation and analysis. Complaints of fluorescent lighting which have any factual basis are generally found to be due to glare from bare lamps in the visual field or to other violations of the principles of good lighting and seeing conditions. Those which involve indictments of the radiant energy emitted by fluorescent lamps find no support in knowledge, in extensive experience or even in sound theory.

Many in the lighting industry recall the suspicions which arose several decades ago when the Cooper-Hewitt mercury-arc was introduced for lighting purposes. It was accused of emitting ultraviolet energy in quantities harmful to the eyes and even to the skin. Its discontinuous spectrum

was also suspected, on the basis of vague unsupported theory, of being detrimental to the visual sense. Even the infrared energy emitted by filament lamps has been accused, and still is occasionally, of harmful biological effects, notwithstanding the fact that no such effects have been established for exposures to infrared energy far greater than those experienced in lighting for seeing.

Even the relatively meager, and spectrally limited, ultraviolet energy emitted by tungsten-filament lamps has been seriously accused of being harmful to the eyes. Bulbs of special ultraviolet-absorbing glass and even "protective" eyeglasses were advocated by some individuals in the early part of the tungsten-lamp era. When the blue-green bulb converted the tungsten-filament lamp into a socalled "daylight" lamp, there was a minor flood of suspicions and complaints. Many of these were ridiculous in varying degrees. The light was accused of being too bluish in color when, as a matter of fact, it is yellowish compared with sunlight. This supposedly bluish light was falsely accused as the cause of various real or imaginary effects.

There are no more fruitful fields for quacks and quackery than those of light, color and radiant energy. There have been extensive promotions of socalled color-therapy notwithstanding the lack of a scientific foundation of acceptable proof. Tinted eyeglasses are recommended where they are not needed. Colored eye-protecting glasses are serving well in arc-welding and elsewhere, but their need is often exaggerated in various fields. (See Plate XIII.)

A certain illuminant may possess definite advantages in specific applications involving appearance of colors, esthetic considerations, or the ability to blend well with daylight. However, common illuminants suitable for general use do not differ significantly in their contribution to visibility. Green light or paper is not "easier on the eyes"

as determined by any known criterion. Purely monochromatic light, such as sodium light, excels in revealing very small details of high contrast, but this advantage does not extend to objects of relatively large visual size. Obviously a monochromatic light is not suitable for general use for the reason that all colors are reduced to shades of the color of the illuminant.[95]

ENVIRONMENT AND EXPOSURE

Too often two basic facts are ignored. One is that natural sunlight and skylight, and Nature's brightnesses and brightness-distributions, have been environmental factors throughout the eons during which life evolved on earth. The other basic fact is that any harmful or beneficial effect is the result of exposure *Et* which is the product of *intensity* and *time*.

Human beings, and their eyes and skin, are the products of eons of evolution and adaptation to environment. There are many known details which support this generalization not only for human beings but for all living things. Probably there are many unknown details which eventually will further reveal the influences of adaptation and the benefits of radiant energy from the sun and sky.

Human eyes did not evolve behind protective eyeglasses and it is ridiculous to assume or to claim that there is harm in ordinary exposures of normal eyes and skin to outdoor daylight. Of course, one may suffer from excessive exposure just as one pays penalties for other excesses. There are pathological eyes and skins, but we are dealing with the overwhelming percentage of normally healthy or near-healthy human beings. We do not give insulin to everyone merely for the reason that a relatively few need it.

Statements to the effect that skylight is too blue, that human eyes need protection from the ordinary brightnesses

outdoors and that energy of certain wavelengths in sunlight and skylight is harmful are specific denials of the great principles of evolution and adaptation to environment. In effect they are indictments of powerful natural forces beside which man is insignificant. But this does not effectively curb man's egotism, particularly if it is incited by the valor of ignorance. In the absence of any facts which would lead us otherwise, we must use natural illuminants and their effects in our safety code. Quantitative measurements will reveal the thresholds for safety and the boundary between beneficial and harmful exposures.

As one continually surveys the scientific and technical literature, too often he finds that lack of quantitative measurements renders otherwise excellent work of little or doubtful value. Many such cases are to be found in studies of physiological and other effects of ultraviolet energy. A recent one will suffice as an example. Wolf [96] exposed the eyes of baby chicks to "the intense radiation" from three 250-watt AH-5 mercury-arcs located at eye-level and only a short distance away. Exposures were standardized at 60 minutes. Apparently he had removed the glass bulbs from the lamps so that the unfiltered energy was that of a quartz mercury-arc. He used various filters, including certain ones suitable for use by arc-welders. He did not present measurements of these excessive intensities, but he concluded that ultraviolet energy of $\lambda 3650$ and shorter wavelengths is harmful. Of course, such energy *can* be harmful in excessive dosages. If he had filtered out all the ultraviolet energy from sunlight and had focused an image of the sun on the eyes for a long enough period, he could conclude that the visible energy in sunlight can be harmful. Certainly he would scarcely have come to the conclusion that we must not look out of a window or go outdoors without the protection of very dark glasses. Wolf concluded that if the

transmission of the media of human eyes is similar to that of the chick's eyes, "the visual mechanism is impaired by ultraviolet light between λ3000 and λ3650." He further states that "Protective means for the eye should, therefore, be filters which absorb the ultraviolet up to λ3650 or sufficiently to prevent injurious effects."

Such careless unqualified conclusions would not have reached the printed page if he had made quantitative measurements and had been adequately impressed by the fact that harmful effects, as well as beneficial effects, depend not only on intensity E but also upon time t. There is a threshold dosage Et in any given case which is on the boundary line between harm and no harm or between benefit and no benefit. Certainly this is adequately proved for energy of all wavelengths in natural sunlight. If the spectral range of ultraviolet energy in artificial illuminants does not exceed that of natural daylight, we have little to worry about. The designer of artificial light-sources can easily control this. If he properly limits the spectral range and the amount of biologically-effective energy per lumen or per footcandle of light, he has on his side the powerful forces of Nature—and even his Creator.

ULTRAVIOLET RADIANT ENERGY

Equipped with special ultraviolet-transmitting glass, tungsten-filament lamps provide enough biologically-effective energy to be useful. However, their erythemal efficiency is relatively low and tungsten lamps with bulbs of ordinary glass do not emit sufficient ultraviolet energy to be harmful in ordinary approved usage. Therefore, the present discussion is initially limited to a comparison of the light and ultraviolet energy, shorter than λ3150, emitted by common fluorescent lamps with that from the sun and sky outdoors.

The intensity and spectral range of erythemal energy emitted by fluorescent lamps depend upon the composition and thickness of the glass tube or envelope and upon the characteristics of the phosphors with which it is coated inside. No reputable manufacturer would make a light-source available for general use without adequately controlling the output of ultraviolet energy. Nevertheless, fluorescent lamps have been extensively subjected to unjust claims and suspicions. Some eyesight specialists and others have advocated tinted eyeglasses to "protect" the eyes from the ultraviolet energy which they have neither measured nor compared with that encountered outdoors in the daytime. Even if these lamps did emit some ultraviolet energy somewhat shorter than λ2900, ordinary colorless eyeglasses would afford sufficient protection from these intensities of erythemal energy which are meager compared with those outdoors.

The spectrum of natural daylight ends in the ultraviolet region somewhere between λ2900 and λ3000, depending upon atmospheric conditions, time of day, season of the year and altitude above sea-level. There are some relatively weak mercury "lines" at λ2925, λ2894 and λ2804 that could be transmitted by a special glass to increase the erythemal efficiency appreciably. However, the energy of these wavelengths which is emitted by ordinary fluorescent lamps is negligible in ordinary usage.

Most of the erythemal effectiveness of ultraviolet energy is due to wavelengths shorter than λ3150. Therefore, to provide the most sensitive comparison of common illuminants, only the energy shorter than λ3150 is used in the present discussion. This range encompasses the characteristic energy of λ3132 in the mercury spectrum.

Sunlight and skylight vary considerably even on clear days and the output from fluorescent lamps varies with the

thickness of the glass, but the data presented in Table XL are sufficiently representative for the present purpose. Such measurements[97] are the result of many years of development of devices and techniques in which one of the author's colleagues, A. H. Taylor, has made many contributions, as discussed in Chapter XV.

In the upper part of Table XL the measurements are presented in microwatts per sq. cm. for energy shorter than λ3150 for the levels of illumination indicated for the various illuminants. It is seen that this erythemally-effective energy is commonly more than a hundred times greater on a clear day outdoors during the midday hours in summer than it is for 50 footcandles of direct or unreflected light from 40-watt 3500° white fluorescent lamps. The ultraviolet energy shorter than λ3150 emitted by 6500° daylight fluorescent lamps is about 2.3 times that from the white fluorescent lamps. This energy is not reflected efficiently by most surfaces. Therefore, unless aluminum reflectors are used, this component of energy is generally greatly reduced in the reflected light.

In the lower part of Table XL the ultraviolet energy shorter than λ3150 is erythemally weighted. Thus these values represent a better picture of the effects upon the skin and the conjunctiva. The values in the third column indicate that sunlight and skylight on a clear day during the midday hours in midsummer are commonly several hundred times as erythemally effective as 50 footcandles of direct light from 3500° white fluorescent lamps.

In the last column of Table XL are presented the actual and relative values of ultraviolet energy shorter than λ3150 *per footcandle*. When the footcandle intensities of sunlight, skylight and fluorescent light are multiplied by these factors, it is seen that there is no factual basis for

worry about the ultraviolet energy from fluorescent lamps for levels of illumination many times greater than 50 footcandles. In fact, workers in lamp factories exposed several

TABLE XL

Intensity of Ultraviolet Energy Shorter Than λ3150 Measured in Microwatts per Sq. Cm. for Certain Levels of Illumination During the Midday Hours on Clear Days in Summer, Compared with That from 40-Watt 3500° K. White Fluorescent Lamps

a. Direct sunlight
b. Skylight, clear blue sky
c. Sunlight plus skylight
d. Direct fluorescent light, 3500° K.

Intensity of ultraviolet energy shorter than λ3150

	Foot-candles	Microwatts per Sq. Cm. Actual	Microwatts per Sq. Cm. Relative	Microwatts per Sq. Cm. per Footcandle Actual	Microwatts per Sq. Cm. per Footcandle Relative
a.	6600	56	70	0.0085	0.53
b.	1900	117	146	0.0620	3.85
c.	8500	173	216	0.0205	1.28
d.	50	0.8	1	0.0160	1.00

Note: Most surfaces do not efficiently reflect ultraviolet energy shorter than λ3150. Therefore, the footcandles due to reflected light are generally accompanied by relatively little of this erythemally-effective energy.

Intensity of ultraviolet energy shorter than λ3150 erythemally weighted

	Foot-candles	Microwatts per Sq. Cm. Actual	Microwatts per Sq. Cm. Relative	Microwatts per Sq. Cm. per Footcandle Actual	Microwatts per Sq. Cm. per Footcandle Relative
a.	6600	7.5	214	0.00114	1.63
b.	1900	15.6	450	0.00820	11.7
c.	8500	23.1	660	0.00272	3.88
d.	50	0.035	1	0.00070	1.00

Note: A six-year record of erythemally-weighted ultraviolet energy in daylight indicates that in midwinter it is about 0.1 that in midsummer at 40° N. latitude.

hours daily to 600 footcandles of light directly from fluorescent lamps have suffered no effects attributable to ultraviolet energy. Actually in this extreme case the intensity of erythemally-weighted ultraviolet energy upon their eyes is much less than the intensity to which their eyes are exposed outdoors during midday on a clear day in midsummer.

The intensity of erythemally-weighted ultraviolet energy on the earth's surface due to skylight is often greater than that due to direct sunlight during midday.[19] In fact, on clear days the sky contributes about as much as the sun during the entire day. This is indicated in Table XL and Chapter II, but an example is helpful.

If a person is standing outdoors on a clear day during the midday hours in summer *with his back to the sun*, the level of illumination at the vertical plane of his eyes may be 500 footcandles due to light from half of a clear blue sky. The ultraviolet energy, shorter than λ3150, per footcandle of direct skylight, may be about 3.85 times as great as that accompanying one footcandle of direct light from white fluorescent lamps. Therefore, from this viewpoint the 500 footcandles of direct light from the sky are accompanied by as much of this ultraviolet energy as 1925 footcandles of direct light from white fluorescent lamps or about 840 footcandles of direct light from daylight fluorescent lamps. No person with normal eyes and skin ever suffered from being exposed to 500 footcandles of skylight outdoors for long periods.

Considering, in addition to this, the fact that most reflecting surfaces have low reflection-factors for this ultraviolet energy shorter than λ3150, there is no factual basis for suspecting that fluorescent lighting can possibly be harmful to normal eyes and skin. Much of the light reaching the eyes is commonly reflected from various surfaces and is often transmitted through materials which absorb erythemally-effective energy. Obviously, fluorescent lighting is safe for levels of illumination many times greater than those of the best fluorescent lighting practice of the present time. If the comparison with skylight is made on the basis of erythemally-weighted ultraviolet energy, as indicated in the lower half of Table XL, it is apparent that

several thousand footcandles of fluorescent light would be no more "harmful" than 500 footcandles of natural light during midday on a clear midsummer day.

It is possible that the conjunctiva may lose some of its adaptation to ultraviolet energy, just as skin does, during the winter months when the sun is at low altitudes and relatively less time is spent outdoors. However, it should become adapted again just as the skin does outdoors. It seems strange that vernal conjunctivitis, occurring in the spring, has been attributed to many other causes and the vitamin era has added new speculations involving deficiencies. However, a simple explanation might be found in the fact that the conjunctiva, as well as the skin, has temporarily lost some of its resistivity due to being predominantly indoors during the winter. If this is true, apparently it soon becomes adapted again as normal skin does. Also there is always the possibility of an abnormality of the skin or of the eyes in some cases which might make a person supersensitive and which may lead to erroneous generalizations. If such a person experiences trouble under fluorescent lighting, he should suffer severely if exposed to skylight outdoors even for a short period of time. Thus it is seen that daylight provides a sort of reference point or plane for many considerations of artificial conditions.

POSSIBLE BENEFITS FROM FLUORESCENT LAMPS

Now let us consider briefly the possibility of providing physiological benefits of ultraviolet energy by means of fluorescent lamps. The author uses the erythemal basis and the term *erythemal energy* for convenience, and this is not to be construed as indicating that erythema in itself is beneficial. This has been adequately discussed in other chapters.

Outdoors average untanned skin receives an MPE dosage in 20 minutes during the midday hours in summer. This dosage is about 400 microwatt-minutes per sq. cm. of erythemally-weighted energy. In Chapter X it has been shown that daily dosages equivalent to one-tenth MPE have been found to prevent and cure rickets. Therefore, let us assume an 8-hour exposure to the direct light from white fluorescent lamps. Any other fluorescent lamp for general use will have its own factor. The erythemally-weighted energy per footcandle delivered directly is 0.0007 microwatt per sq. cm. In 8 hours the equivalent erythemal dosage would be 0.266 microwatt-minute per sq. cm. for each footcandle. A sub-erythemal dosage equivalent to 0.1 MPE would result from being exposed to 150 footcandles of direct light from white fluorescent lamps.

Inasmuch as fluorescent lighting has so far advanced that there are many installations of 50 footcandles and some of 100 footcandles, it would appear that the medical profession and others interested in the health and general welfare of human beings might well turn their attention to the possible physiological beneficial effects of the erythemal energy emitted by the fluorescent lamps now in common use. If a daily dosage equivalent to one MPE is desired, it would be provided by 1500 footcandles supplied by white fluorescent lamps for 8 hours.

Considering the fact that daily sub-erythemal dosages from tungsten-filament lamps in special bulbs have actually cured and prevented rickets in babies and have prevented rickets in growing chicks, the possibility of biological benefits from ordinary fluorescent lamps is intriguing. The output of ultraviolet energy shorter than $\lambda 3150$ from daylight fluorescent lamps is about twice that from white fluorescent lamps. Erythemally weighted, the difference is still greater. Therefore, only a few hundred footcandles directly from daylight fluorescent lamps should provide an equivalent MPE dosage in 8 hours.

If a fluorescent lamp for lighting purposes were made to deliver only 10 times as much erythemally-weighted energy as a white fluorescent lamp, in 8 hours 15 footcandles would provide an equivalent dosage of 0.1 MPE and 150 footcandles would supply an equivalent dosage of one MPE. If the fluorescent lamps were used in aluminum reflectors which delivered the light and radiant energy directly to the occupants, the foregoing values would not have to be increased appreciably. However, if the reflectors are coated with baked or porcelain enamel, the erythemal energy would suffer considerable absorption in the process of reflection.

Here it is well to repeat that an MPE dosage is received outdoors during midday on a clear day in summer in about 20 minutes and in about 3 hours in midwinter. A dosage equivalent to 0.1 MPE is obtained in about 2 minutes in summer and in about 20 minutes in winter. Obviously, the output of erythemal energy emitted by fluorescent lamps can be increased greatly beyond the present values and still be well within the range of safety and comfort while providing the beneficence attributed to natural daylight outdoors. The erythemal energy is readily controllable in spectral range and in intensity by the composition and thickness of the glass tube or bulb. By altering these so that the erythemally-weighted energy emitted with each lumen would be about 10 times that emitted by the present white fluorescent lamp, it appears that human beings exposed no more than 8 hours to 50 to 100 footcandles would receive benefits which accrue from reasonable exposure outdoors.

It is time to turn the attention from imaginary harmful effects of fluorescent light to the promising benefits of

levels of illumination which are needed for high visibility and easy seeing. Sunlamps have their place for specific treatments and in dual-purpose lighting. But the ideal illuminant and lighting system is one which plays the dual role. These appear to be within reach. Certainly civilized human beings confined indoors for long periods daily are entitled to whatever benefits summer sunlight bestows outdoors. They will receive these benefits best if they come simultaneously with adequate light and good lighting. Experience shows that such benefits should be bestowed automatically, without effort and thought on the part of the recipients. Some persons will take the trouble to use sunlamps, but the overwhelming majority will not.

VISIBLE RADIANT ENERGY

The illuminants in common use are natural sunlight and skylight, which vary considerably in spectral distribution of energy, the yellowish light from tungsten filaments with its continuous spectrum, and the light from fluorescent lamps of various color-temperatures which consists of the discontinuous spectrum of mercury superposed on the continuous spectrum of the fluorescent phosphors. The spectral distributions of energy of representatives of these four illuminants are presented in Fig. 98. It is obvious that they differ markedly in spectral character. However, from an extended experience with all the available criteria, the author is forced to the conclusion that these illuminants do not differ significantly in their effect upon visual acuity and upon the visibility of objects and tasks. Furthermore, no acceptable criterion has revealed that any of these illuminants is easier on the eyes than any of the others. Criteria of ease of seeing indicate no significant difference among them. None has been proved to be harmful. The misuse of the sun, sky, tungsten or fluorescent lamps in lighting can result in glare and poor seeing conditions. However, the causes are not inherent in the light, but arise from its misuse.

One of the perennial suspects among the various characteristics of common illuminants is the discontinuous spectrum as exhibited by the mercury-arc of the older type. As is well known, its visible energy is confined almost entirely to four spectral "lines" in the regions indicated by the four rectangles projected above the continuous spectrum *D* in Fig. 98. Between these lines of the spectrum of the Cooper-Hewitt mercury-arc there are gaps in which little or no energy is radiated. This discontinuous spectrum has been much berated without any proof upon which to base a suspicion.

If a white surface is illuminated by the light from this mercury-arc with a discontinuous spectrum, the visual sense appraises the surface as white with a bluish or greenish tint. The eye does not "know" whether this white surface is illuminated by an illuminant with a discontinuous or a continuous spectrum. Actually the visual sense is unable to determine the spectral characteristics of common illuminants plotted in Fig. 98, for equal intensities of illumination; that is, for equal footcandles on a perfectly white surface. When the spectral energy is converted into luminous sensation, the differences among the four illuminants of Fig. 98 are greatly reduced. This is illustrated in Fig. 105 by the spectral luminosity curves of the same illuminants.

Throughout the realm of physiological optics there is no fact which supports the suspicion that this discontinuous spectrum is harmful in any way. Speculators seem to lose sight of the fact that the visual sense "synthesizes" visible energy of various wavelengths. Furthermore, uncounted thousands of persons have performed critical seeing for many years under mercury-arc light with its discontinuous

spectrum, without any discovery of ill effects by ophthalmologists or other qualified specialists. An ophthalmologist who questions a discontinuous spectrum or any other aspect of light to which millions have been exposed might

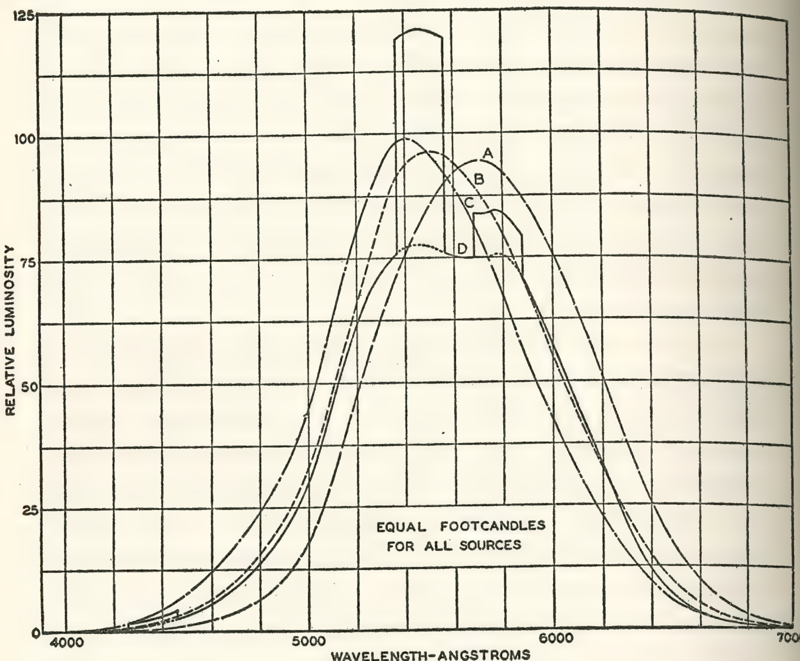


FIG. 105. The spectral luminosity curves of four common illuminants corresponding to the spectral distribution curves in Fig. 98. *A*, tungsten filament 2850° K.; *B*, natural sunlight plus skylight 6000° K.; *C*, zenith blue sky 60000° K.; *D*, daylight fluorescent lamp 6500° K.

seriously wonder why the effect has not been isolated and the cause identified.

The spectral characteristic of the visible energy from fluorescent lamps is a continuous spectrum upon which the discontinuous spectrum of mercury is superposed. As seen in *D* in Fig. 98, the spectrum of the visible energy emitted by the daylight fluorescent lamp is continuous but irregular

on account of the mercury lines. Certainly if no positive evidence of harmful effects of the discontinuity of the mercury spectrum exists, there is no cause for suspecting the continuous though irregular spectrum of the light from the fluorescent lamps in common use. Furthermore, millions of persons have already performed critical seeing for long periods under fluorescent lighting without any scientific proof of harmful effects *due to the spectral character of the light.*

One common source of confusion in this respect is the failure to discriminate between spectral character of light and glare due to brightness and brightness-contrasts in the visual field of the worker. Incidentally, it has not been established that light of one spectral character is any more or less glaring than light of another spectral character. On the contrary, the evidence of some researches indicates that there is no significant difference in this respect among illuminants differing moderately in color. The illuminants commonly in use differ greatly in spectral character, but only very moderately in color. In fact, all are unsaturated tints rather than pronounced colors. Therefore, glare from common illuminants must be considered a matter of brightness or quantity of light rather than a matter of the kind of light.

Recently Harmon [98] has revived some of the old speculations and has added some new ones arising from the current vitamin era. He concluded that fluorescent light was detrimental to the eyes from observations which could not possibly provide such proof and from theorizing which was unsound. In comparing tungsten-filament light with fluorescent light, he did not control glare. In his major investigation of lighting he dealt with a direct system of fluorescent lighting with bare lamps in the visual field of the workers and an indirect system of tungsten-filament

lamps. From the viewpoint of harmful effects of glare, indirect lighting with filament lamps is obviously better than direct lighting with fluorescent lamps when some or many of the latter are visible in the visual field of the workers. These were the types of installations from which complaints arose which Harmon investigated. However, no conclusions in regard to the effect of spectral character of light upon the eyes are sound unless all other factors are controlled and the seeing conditions are identical with the exception of the spectral characteristics of the illuminants which are being compared.

Vitamins are among the great contributions of science in the present era. Appreciation of their beneficence is not altered by the extravagance of some claims and of some of the promotional efforts toward their commercialization. A deficiency in riboflavin is apparently revealed by vascular signs around and within the edge of the cornea. The eyes are "blood-shot" in this region. Some excellent work has been done with this criterion, as, for example, on pilots flying over water in the daytime. The brilliant imperfect images of the sun that are reflected from the water's surface are very glaring. Ariboflavinosis, or a deficiency of riboflavin, has been indicated as one of the results of this glaring condition. Some believe that this is due directly to exposure to light. However, no systematic research has proved that it depends upon the spectral character of the visible energy, at least within the variations of spectral character among common illuminants. Here again glare due to brightness is a real culprit, and it may be the sole culprit. We know that the effects of glare are far reaching. It not only causes eye-strain and eye-fatigue, but also tenseness and annoyance with various results. Therefore, the effects of glare pervade the physical, physiological and psychological realms of a human being.

In some speculations it is implied that if exposure to light causes a riboflavin deficiency, this is a harmful or deleterious effect. One might just as well conclude that walking or working causes harmful effects through the "deficiencies" which result. We eat, drink, rest and sleep to make up deficits due to working—and living. Degeneration and regeneration in uncounted processes are continually going on in the living human being. However, in considering exposure of eyes to light, we should not ignore normal regeneration or lose sight of the need for adequate light and proper lighting. There is adequate proof that inadequate light and improper lighting and other aspects of poor seeing conditions adversely affect the human being and human resources. Medical, health and welfare authorities have lagged far behind in recognizing the possibilities of modern light-sources.

Harmon theorized with the absorption spectrum of riboflavin which extends from the middle ultraviolet region through the violet, blue and blue-green portions of the visible spectrum. In other words, it indicates that riboflavin absorbs visible radiant energy shorter than $\lambda 5100$ to some degree. He then makes a not uncommon error in interpreting the meaning of the absorption spectrum and the Grotthus-Draper Law. He assumes that, violet, blue and blue-green light being absorbed by riboflavin, visible energy of all these wavelengths destroys riboflavin. It is true that radiant energy must be absorbed if it is to produce an effect, whether this effect is detrimental or beneficial, undesirable or desirable. However, the converse is not true. In other words, energy which is absorbed does not necessarily cause any other effect than to heat the material.

A red fabric may fade upon exposure to an illuminant. Its absorption spectrum obviously extends from the middle of the visible spectrum through the green, blue and violet

and into the ultraviolet regions. It is not necessarily true that energy of all the wavelengths throughout this absorption spectrum causes the fading. In a given case only the ultraviolet energy may be primarily responsible for the fading. The absorbed energy of other wavelengths may produce no photochemical effect. It may only raise the temperature of the red fabric.

In the case of a deleterious effect, the absorption spectrum, in a sense, only indicates the woods in which the culprit is concealed but it does not necessarily indicate the tree behind which the culprit is to be found. The absorption spectrum of riboflavin does not prove that energy of any wavelength which is not entirely transmitted causes such a photobiological effect as the destruction of riboflavin. Furthermore, there is always the natural regenerative process to be considered just as in the case of fatigue and other results of being an active human being utilizing its resources in many ways.

Initially Harmon seems to have been insufficiently concerned with glare in his observations and erroneously influenced by the absorption curve of riboflavin. The latter influenced his speculations to the extent that he actually viewed tungsten-filament light favorably owing to its relative paucity in the short-wave region of the visible spectrum. Owing to a greater abundance of short-wave visible energy in fluorescent light, he speculated that this illuminant was less satisfactory than tungsten-filament light. No proof of this is available in practice and none exists in theory. In addition, it is well to repeat that millions of persons have been working for long periods under fluorescent light just as many millions have worked and still work under tungsten light. If there is a significant difference in their photobiological effects, it seems reasonable to believe

that it could not escape discovery by or through this mass experience.

There is still another important aspect to any speculation in regard to the blue component emitted by daylight

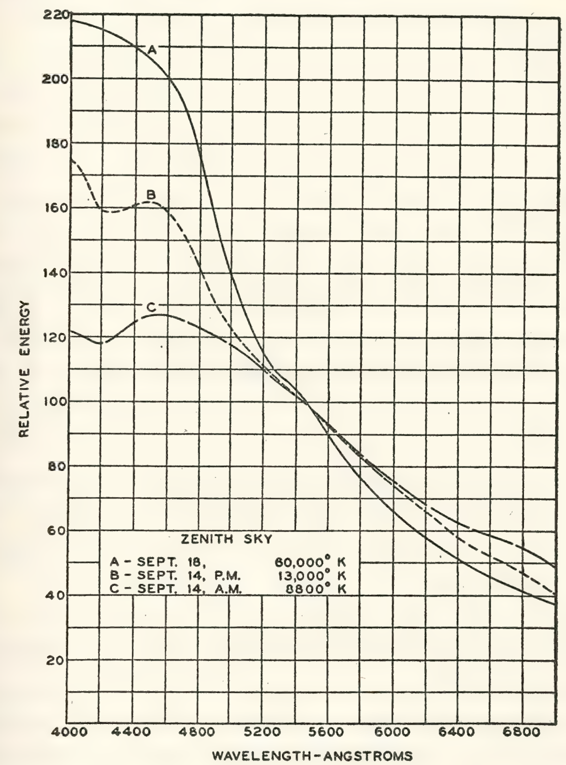


FIG. 106. Spectral distribution of visible energy in skylight varies considerably during the same day and markedly on different days.

fluorescent lamps. Let us consider skylight from a clear blue sky. In Fig. 98 it is seen to contain a greater abundance of short-wave visible energy than light from daylight fluorescent lamps for equal intensities of illumination. In Fig. 106 are three typical spectral distributions of blue skylight,

determined by Taylor and Kerr,[99] which reveal an abundance of energy which has been theorized as being undesirable or harmful. Countless billions of persons for centuries have been exposed for long periods outdoors to the light from the sky. In fact, until relatively recently, skylight through windows and other openings has been the universal indoor illuminant. Even today countless millions read and perform other critical tasks of seeing near windows for long periods daily. If light from the fluorescent lamps in common use is detrimental in any way owing to the short-wave visible energy—blue and violet—blue sky should be far more detrimental owing to its greater blueness. When one takes into account the levels of illumination, such a speculation becomes still more attenuated. Apparently such speculators are not acquainted with these facts. Actually there is no evidence upon which to throw aside the great principles of evolution and adaptation. If human eyes are not adapted to natural skylight, are they adapted to anything? Obviously, it is quite a responsibility to indict the spectral characteristics of fluorescent lamps in common use. Actually, natural sunlight and skylight will have to stand trial too.

In Fig. 107 are plotted in black circles the color-temperatures of various phases of daylight outdoors as determined by Taylor and Kerr.[99] They also determined the spectral distributions of energy. The solid line represents color-temperatures of the theoretical black-body. It is seen that daylight does not depart much from the black-body curve, but its color-temperature varies enormously from 4975° K. for a low-altitude sun to 60,000° K. for a clear blue zenith sky. Certainly anyone who considers the light emitted by 6500° K. daylight lamps to be too blue, and for this reason detrimental to eyes, is scarcely familiar with the spectral quality of natural light.

Harmon also claimed to be able, by a superficial examination of the eyes, to determine whether the subject had been working under tungsten or fluorescent light. Examination of nearly 40 subjects in the presence of the author

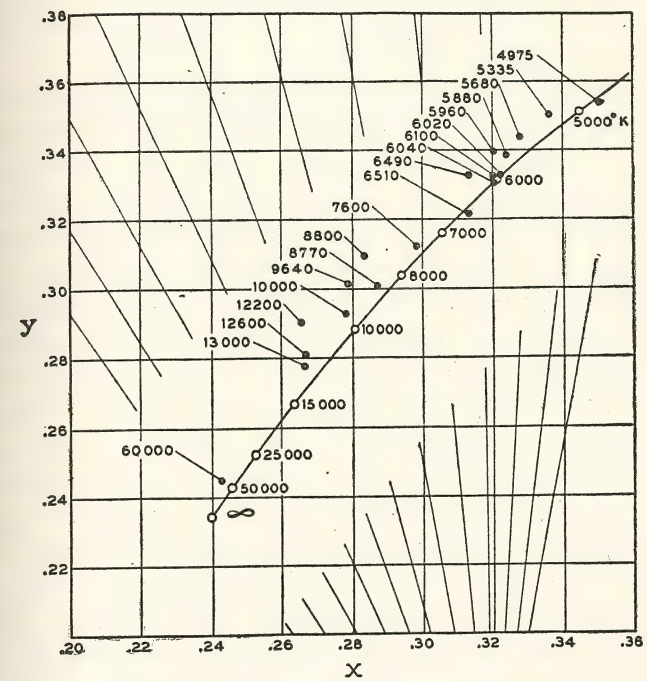


FIG. 107. This section of the I.C.I. colorimetry diagram shows the location of the integral color of various phases of daylight with respect to the black-body color-temperatures represented by the unbroken curved line. (A. H. Taylor and G. P. Kerr.)

and some of his colleagues resulted in complete failure. Two subjects whose eyes were exposed to 600 footcandles of light from daylight fluorescent lamps, in the course of their work in a lamp factory, exhibited no visible symptoms which were supposed to be the result of such exposure. Inasmuch as Harmon has not pursued this matter to a con-

clusion, it appeared necessary to devote some space to this discussion. Fluorescent lamps are such a great advance in light production that they deserve to be appraised by facts. They deserve to be defended against speculations and indictments that are neither proved nor retracted.

INFRARED RADIANT ENERGY

In the use of light primarily for seeing purposes, infrared radiant energy is of interest chiefly from the viewpoint of the total radiant energy which accompanies each lumen of light flux. In other words, the "heating effect" per footcandle is important to human occupants and to various materials. High levels of illumination are practicable only to the extent that the heating effects are within reasonable bounds. There is no direct evidence that intensities of infrared energy which are tolerated by human skin of the face are harmful to the eyes. However, the author [100] computed the energy densities in the eye media which accompany light and showed the much greater values for tungsten-filament light than for daylight. Luckiesh and Moss [101] found no significant differences in various visual functions when using tungsten light with and without filtering out 74 percent of the total radiant energy. They used intensities of illumination as high as 100 footcandles on white backgrounds of printed matter and test-objects. No appreciable effect was found on the rate of involuntary blinking, diameter of the pupil, convergence reserve of the external ocular muscles, rate of reading and the time required to perform a specially difficult visual task.

These tests do not include the possible effects upon the eye media of long-wave infrared energy for many years. At any rate an artificial illuminant cannot be seriously suspected if it is comparable in "coolness" with daylight. Here again fluorescent lamps represent great progress as

indicated in Table XLI. The approximate intensities of radiant energy per footcandle were measured in microwatts per sq. cm. for direct light from the sources. It is seen that fluorescent light compares favorably with natural sunlight, and that tungsten-filament light is accompanied by more than 5 times as much energy. In "coolness," skylight ranks

TABLE XLI

Approximate Intensities of Radiant Energy per Footcandle for Various Illuminants

	Microwatts per Sq. Cm. per Footcandle	
	Actual	*Relative*
Clear skylight through ⅛-inch glass	4.9	0.61
Sunlight, midday midsummer	9	1.12
Sunlight through ⅛-inch glass	7.5	0.94
Fluorescent lamp, 40-w, 3500° K.	8	1.00
Same through ⅛-inch clear glass	3.5	0.44
Fluorescent lamp, 40-w, 6500° K.	10	1.25
Same through ⅛-inch clear glass	4.5	0.56
Tungsten-filament lamp, 60-w.	55	6.9
Tungsten-filament lamp, 100-w.	45	5.6
Tungsten-filament lamp, 200-w.	40	5.0

highest. Naturally the water vapor in the atmosphere aids in "cooling" sunlight and skylight, but a major fact is that human eyes evolved to utilize most efficiently the wavelengths of energy that are most abundant in average daylight.

A sheet of clear glass considerably reduces the radiant energy per footcandle from fluorescent lamps. Actually, fluorescent light after passing through this additional sheet of glass is as cool as natural skylight entering a room through a glass window. The light from a 40-watt fluorescent lamp owes its coolness to the fact that about 7.4 watts are radiated as visible energy and about 10.9 watts are radiated as infrared energy. The remaining 21.6 watts, or about 54 percent of the total 40 watts, are lost by convec-

tion and conduction. Of course, this energy heats the room, but practically none of it passes through a sheet of glass.

Really cool light is supplied by fluorescent lamps. This means relatively high levels of illumination are practicable without discomfort to human beings. Some tests with blindfolded persons indicated that they were just able to detect the heating effect of about 600 footcandles of fluorescent light on the bare skin of the forehead. They barely detected 125 footcandles of light from 100-watt tungsten-filament lamps.

SHORT-WAVE INFRARED ENERGY

Infrared radiant energy in the spectral range adjacent to the visible spectrum is of particular interest to human beings and in many applications of radiant energy. Water transmits this energy fairly well. A depth of 4 mm. or about 0.15 inch does not transmit appreciable energy longer than $\lambda 14{,}000$. Eye media and human flesh, with their very large content of water, absorb long-wave infrared energy but transmit fairly well the *near-infrared* energy. The spectral transmission-factors of human flesh and of various glasses, including copper red and cobalt blue, are presented in Fig. 108. The socalled Vitaglass is fairly representative of common clear glasses in the visible and infrared regions. It is seen that a source of radiant energy for heating human flesh to a depth should produce energy of $\lambda 6000$ to $\lambda 16{,}000$ fairly efficiently. Tungsten-filament lamps are quite efficient sources of this long-wave visible and short-wave infrared energy. Inasmuch as human flesh is colored red by the blood, a red glass may be used for the bulb of a tungsten lamp. This greatly reduces the light without comparably reducing the energy which penetrates flesh. Even a cobalt blue glass transmits the deep red and the short-wave infrared energy quite efficiently.

The efficacy of various sources of infrared energy for heating human flesh at a depth is well illustrated in Fig. 109. The spectral region of interest is from about $\lambda 6000$ to $\lambda 16{,}000$. This is represented by the vertical broken lines. It is apparent that the sun and the 500-watt tungsten-filament lamp are efficient sources of the radiant energy

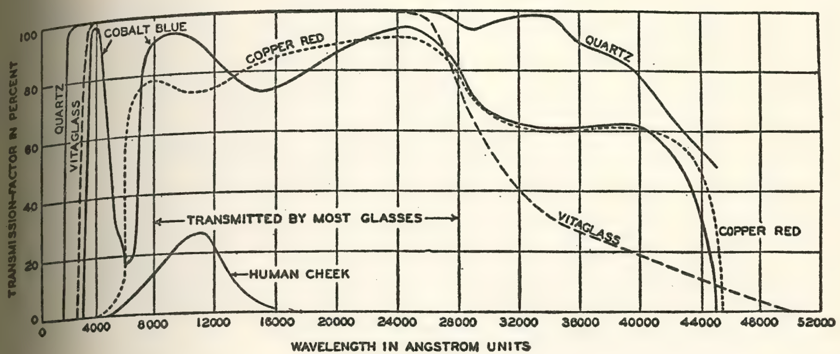


FIG. 108. Spectral transmission of human cheek and of clear and colored glasses.

that penetrates water and bodily tissue. The carbon-filament lamp is less efficient and non-luminous heaters and boiling water (hot towels) are of extremely low efficiency. These low-efficiency devices heat the superficial layers of the skin where the sensory nerves are abundant and cause discomfort or pain. The flesh at greater depths is heated by conduction. As a consequence, heating at a depth is achieved less efficiently and with much greater discomfort to the subject than when sunlight and high-efficiency tungsten lamps are used. (See Chapter XVI)

The insert in Fig. 109 indicates the percentages of total energy, radiated by these 5 sources, in the spectral region in which water, eye media, and human flesh are more or less transparent. It is seen that 53 percent of the total

energy emitted by a 500-watt tungsten-filament lamp is in the spectral range of interest in heating bodily tissue to a depth. The carbon-filament lamp, commonly used for this purpose, emits only 26 percent of its total energy in this spectral region. Hot towels are the least efficient and most

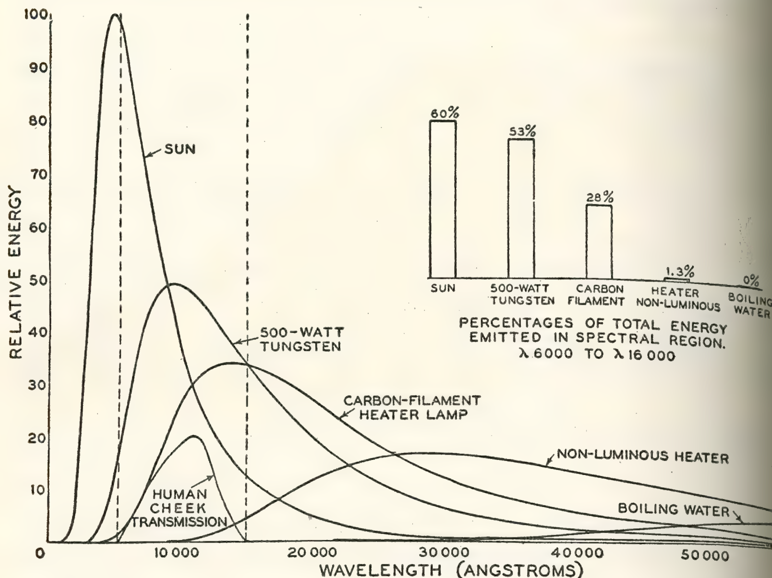


FIG. 109. Illustrating the relative amounts of energy emitted by various sources in the spectral region in which water and human flesh are fairly transparent.

painful way of heating bodily tissue. Not only should tungsten filaments be used for the sake of efficient production of the desired short-wave infrared energy, but also for the comfort of the user. In local applications as well as in "bath cabinets," the subject will be noticeably more comfortable when more of the heating of bodily tissue is achieved by transmission and less by conduction. Tungsten-filament lamps of the higher wattages are outstandingly superior for this purpose.[102]

This point is illustrated further by comparing the absorption and transmission of the energy emitted by carbon- and tungsten-filament lamps. In Fig. 110 the boundary curve illustrates the spectral distribution of energy emitted by an ordinary carbon-filament lamp operat-

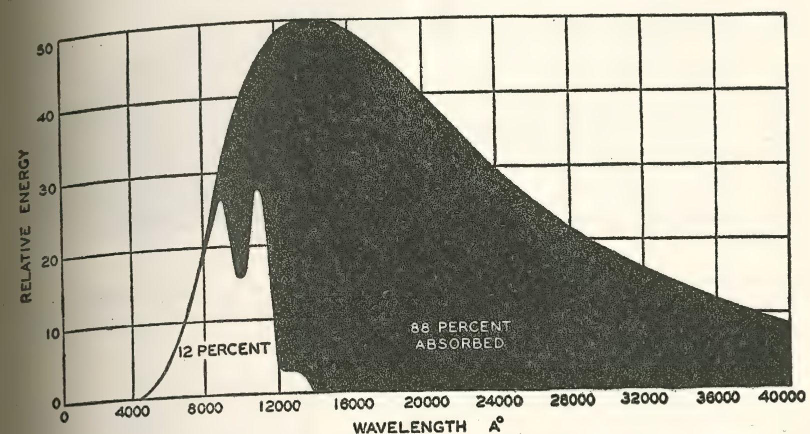


FIG. 110. Spectral emission of energy by a carbon filament operating at 2090° K. and the spectral absorption and transmission of a one-inch thickness of clear water.

ing at a color-temperature of 2090° K. The absorption of one inch of water is indicated by the black portion for the various wavelengths. Only 12 percent of the total incident energy is transmitted by the one-inch depth of water.

In Fig. 111 is illustrated the spectral distribution of energy emitted by a 500-watt tungsten-filament lamp operating at a color-temperature of 2900° K. Only 70 percent of the total incident energy is absorbed by one inch of water. The remaining 30 percent can proceed to greater depths to be absorbed.

In Fig. 112, data are presented for various tungsten-filament lamps for various depths of water. Such data have

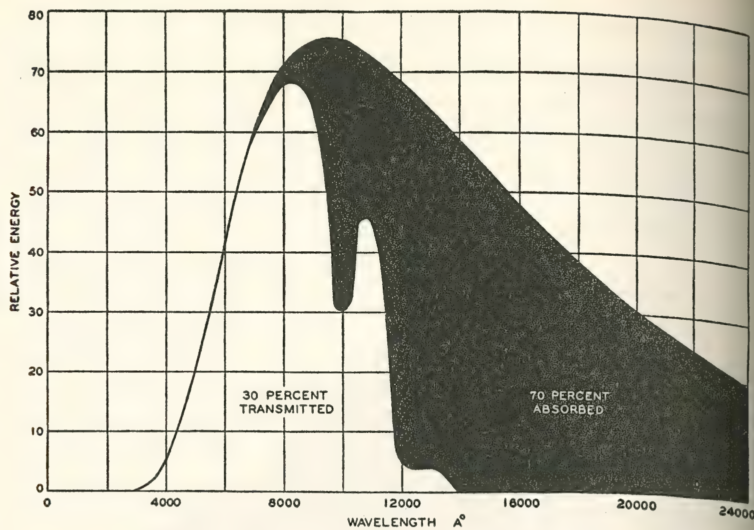


Fig. 111. Spectral emission of energy by a 500-watt tungsten-filament lamp operating at 2900° K. and the spectral absorption and transmission of a one-inch thickness of clear water.

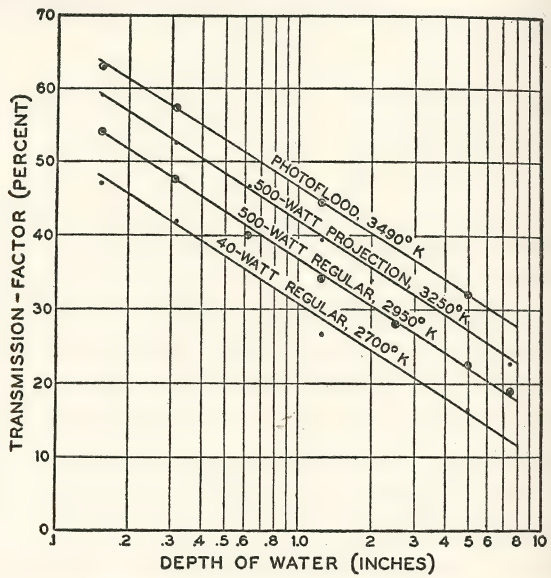


Fig. 112. Showing the transmission-factors of various depths of clear water for the total energy emitted by various tungsten-filament lamps.

many practical applications. They reveal how much energy emitted by these lamps can be absorbed by clear water. They also indicate roughly how much energy can reach the depths of eye media and bodily tissue. They indicate

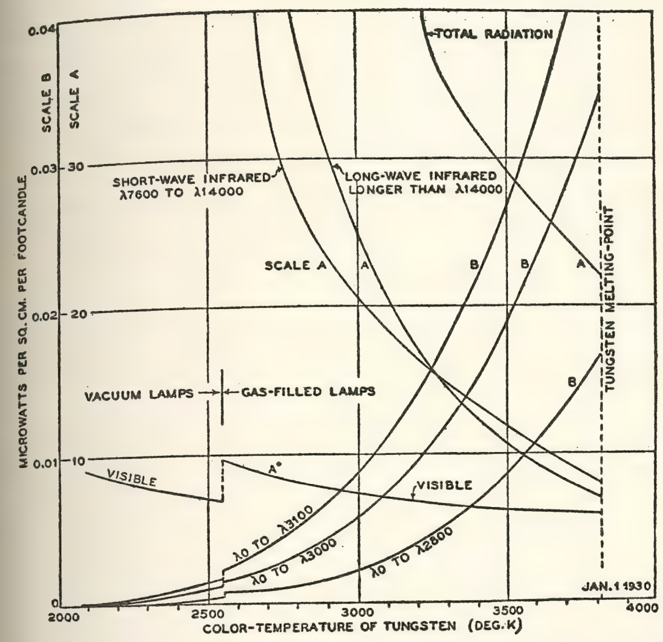


Fig. 113. The influence of color-temperature of tungsten filaments upon the intensity of radiant flux of various spectral ranges received per footcandle by each sq. cm. of surface. The flux is assumed to come directly from the filament with no absorbing bulb intervening.

that for therapeutic purposes and bath cabinets the more desirable tungsten-filament lamp is that operating at the higher temperatures.

In Fig. 113 is plotted the energy in various spectral ranges which would accompany each footcandle delivered directly from a tungsten-filament at various temperatures provided the bulb absorbed no energy of any wavelength.

Of course, this is not true for the ordinary glass bulb absorbs some of the ultraviolet energy and determines the short-wave spectral limit of the emitted energy. It also absorbs some long-wave infrared energy. Therefore, the data plotted in Fig. 113 represent the energy of various spectral ranges which could accompany each footcandle directly from the filament if it were enclosed in a perfectly transparent bulb. These data are valuable (1) in ascertaining the effect of color-temperature of the filament, (2) in determining the amount of erythemal flux that could be obtained and (3) in showing the amount of energy that could be absorbed by water.

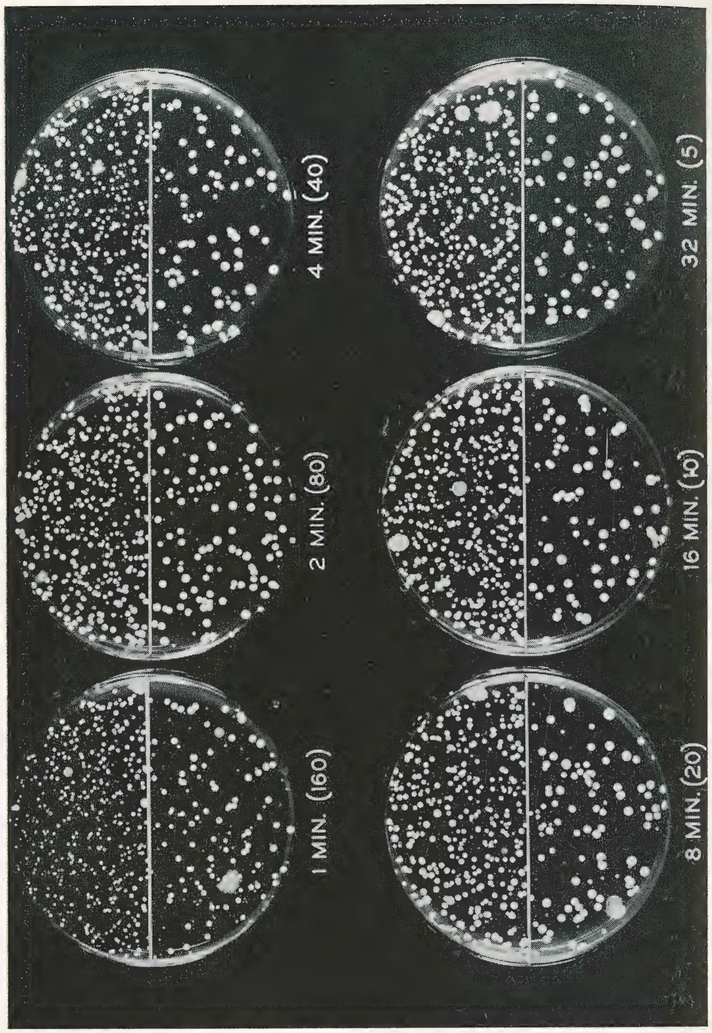


PLATE XIV. The petri dishes simultaneously collected air-borne micro-organisms in a poultry house. Then the lower halves were exposed separately, for the minutes indicated in each case, to intensities of germicidal flux in microwatts per sq. cm. indicated by the number in parentheses. The exposure or dosage of the lower halves was 160 microwatt-minutes per sq. cm. It is seen that the reciprocity law holds over this range of 1 to 32.

Chapter XIV

Reflection and Transmission

THE PRODUCTION of ultraviolet energy for different purposes is a matter of exercising various controls that are possible or available. The first control is in the very source of the energy. Carbons can be impregnated with various materials which determine the emission spectrum. This is illustrated for two carbon arcs in Fig. 5. Tungsten filaments can be operated at different temperatures and mercury-arcs can be operated at different pressures. The output of ultraviolet, visible and infrared energy is thereby controlled to a considerable extent. The most useful sources of ultraviolet energy at the present time are mercury-arcs or mercury-vapor lamps. The emission spectra of these sources are largely determined by the vapor pressure in the enclosed space. As discussed in other chapters, the mercury-arc, operating at an extremely low pressure emits most of its ultraviolet energy in the neighborhood of $\lambda 2537$. This is the basis of modern germicidal sources and of fluorescent lamps. The other extreme is represented at the present time by the high-pressure mercury-arc illustrated in Fig. 9. It emits a continuous spectrum upon which the characteristic discontinuous spectrum of mercury is superposed. These have been discussed in various chapters, including Chapter X.

To some extent control of the production of ultraviolet energy can now be exercised by means of fluorescent materials known as phosphors. Some of these, when excited by energy of $\lambda 2537$, which is efficiently produced by low-pressure mercury-arcs, emit radiant energy in the ultraviolet spectral region. This is another means of controlling the production of ultraviolet energy. The fluorescent sun-

lamp or F sunlamp is a practical example of the application of this principle.

After this energy is produced, the short-wave limit of the energy emitted by the complete lamp is determined by the composition and thickness of the glass envelope if there is one. The short-wave limit of the radiant energy may be varied from λ1800, by the use of quartz, throughout the ultraviolet region by the use of different ultraviolet-transmitting glasses. This type of control is very important in adapting the different sources to specific uses.

The utilization of the ultraviolet energy involves the reflection-factors of various materials. These vary from a few percent to about 90 percent. Naturally highly efficient reflectors are desirable for directing the ultraviolet energy to its task. It is also desirable in certain practices to absorb this energy after it has done its work. Therefore, reflecting and absorbing media are very important in the use of ultraviolet energy. For three decades the author and his colleagues have been investigating these possibilities by means of sensitive measuring devices. As a consequence, with the cooperation of manufacturers and finishers of materials, adequate control can now be achieved in the utilization of ultraviolet energy.

Interest in reflecting media is chiefly confined to the spectral regions of λ2537 for germicidal energy and λ2967 for artificial sunlight, and in some cases to the visible spectrum. Interest in transmitting media is not only confined to the short-wave cut-off but to the steepness of the spectral transmission-curve near the point of cut-off. These and other pertinent facts are discussed and illustrated. Reflecting materials are of interest to more persons than transmitting media, for the former are involved in equipment designed for the sources and in the various uses of ultraviolet energy. Total and spectral transmission of special glasses, which

become a part of the lamp, are of chief interest to the manufacturer of the producers of ultraviolet energy. However, the efficacy of ultraviolet energy in many special applications depends upon the transmittance of erythemal energy by various materials and upon the transmittance of

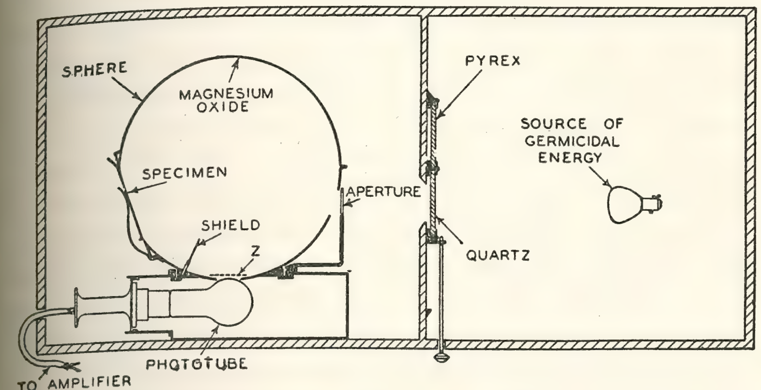


Fig. 114. Absolute integrating reflectometer for measuring reflection-factors of materials for energy of λ2537.

germicidal energy by air, water and other liquids which are to be disinfected.

REFLECTION OF ULTRAVIOLET ENERGY

With the exception of work published by a colleague, A. H. Taylor,[103] the author is unaware of any devices and methods which completely integrate the ultraviolet flux reflected by a surface. This is the proper means of determining reflection-factors for ultraviolet energy as it is for light. Recently Luckiesh and Taylor [104] have described two of these integrating reflectometers.

In Fig. 114 is illustrated an absolute integrating reflectometer for measuring the reflectance or reflection-factor of materials for energy of λ2537. Flux of λ2537 emitted by

a special source, RP-12, enters the sphere through an aperture ¾ inch in diameter and falls on the specimen mounted over a larger aperture at the opposite side of the sphere. The inner surface of the sphere is smoked with magnesium oxide which has a high reflectance throughout the ultraviolet region of practical interest. An opaque shield, also smoked with magnesium oxide, prevents any first-reflected flux from the specimen from directly reaching the phototube. After the proper readings have been made, the sphere is rotated 90 degrees about its vertical axis. This brings into proper position another aperture ¾ inch in diameter through which the λ2537 flux enters the sphere and falls on the opposite wall of the sphere at a point not screened from the phototube. The flux reaching the phototube in the first case is less than that in the second case by the amount absorbed by the specimen under test. The ratio of the phototube current in the first position of the sphere to that in the second position provides a direct measure of the reflectance or reflection-factor of the material.

The differential shutter of pyrex and quartz limits the measurements to the spectral region below λ3000. When using a source which radiates nearly all its energy in the region of λ2537, the reflectance is determined for that wavelength. In this case the differential shutter is useful in establishing the zero reading for there is some long-wave ultraviolet energy emitted by the source. This is not transmitted by the pyrex but is transmitted by the quartz.

We have used a phototube with a cathode of cadmium-magnesium alloy which is sensitive to energy of λ2537. However, its sensitive surface may not properly integrate the flux incident from all directions. Therefore, a plate of clear glass coated with zinc silicate Z is placed over the aperture above the phototube and an RCA-929 phototube is used to measure the brightness of the fluorescing phos-

phor. This has proved to be an excellent improvement and the phosphor surface Z is dull enough to integrate fairly well the flux from various directions.

The absolute reflectometer illustrated in Fig. 115 is used with a quartz monochromator for measurements of

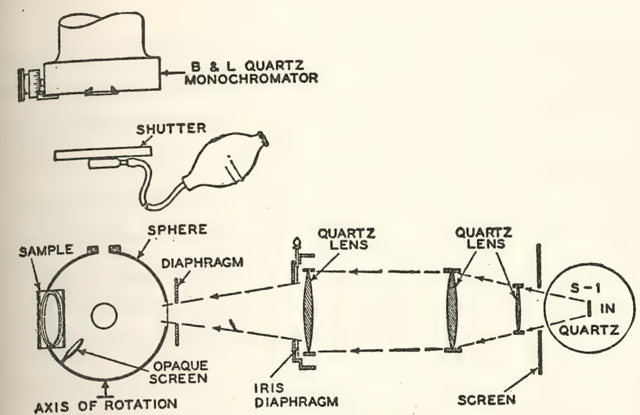


Fig. 115. Absolute reflectometer used with a Bausch and Lomb No. 2800 quartz monochromator for the measurement of the reflectance of materials for energy of various wavelengths throughout the ultraviolet region and to the middle of the visible spectrum.

reflectance of energy of various wavelengths throughout the ultraviolet and to the middle of the visible spectrum. By means of quartz lenses the arc of an S-1 tungsten mercury-arc, in a clear quartz bulb, is focused on the test sample through an aperture in the sphere which is smoked inside with magnesium oxide. The quartz monochromator views a small area of the inside wall of the sphere on the axis of rotation. Photometrically the operation of the sphere is the same as that illustrated in Fig. 114, the monochromator being substituted for the phototube. Measurements of intensity of energy of various wavelengths are made by means of an RCA-935 phototube and suitable amplifier.

These two devices are quite sensitive, and many measurements of total and spectral reflectance have been made. The data presented here are confined to materials useful in controlling ultraviolet energy and to representative materials encountered or which are or may be useful in practice.

Many years ago we found that aluminum reflectors

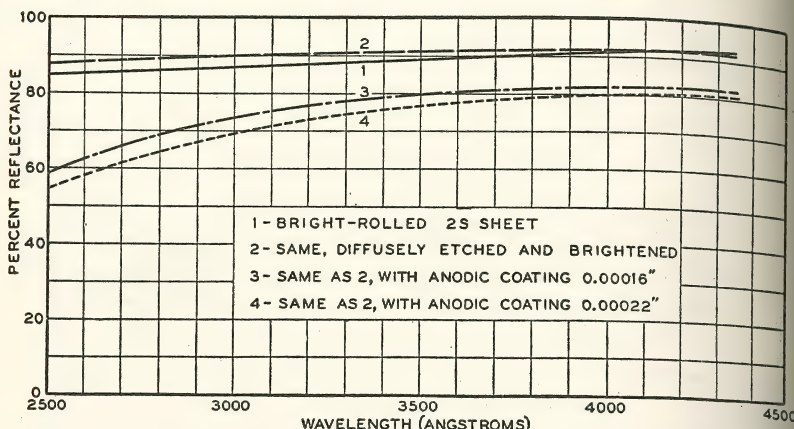


Fig. 116. Spectral reflectance of aluminum with and without Alzak treatment. Samples were furnished by Alcoa Research Laboratories.

made of the same sheet aluminum, by spinning and by pressing, had slightly different reflection-factors for energy of λ2967. This led to further considerations of the influence of the character of the surface. Since that time aluminum surfaces have been subjected to various treatments to increase their reflectance of ultraviolet energy. The Alzak process [105] has come into extensive use in the treatment of sheets and reflectors of aluminum. In this process the first part of the treatment, known as electrolytic brightening, removes impurities from the surface. The second treatment applies a thin oxide coating which protects the surface somewhat from weathering effects but reduces the

reflection-factor somewhat. This reduction is greater for ultraviolet than for visible energy.

Fig. 116 illustrates the effects of the two steps of the Alzak process on the spectral reflectance of a given specimen of aluminum sheet. The oxide thicknesses of 0.00016 and 0.00022 inch for diffusely etched aluminum are within

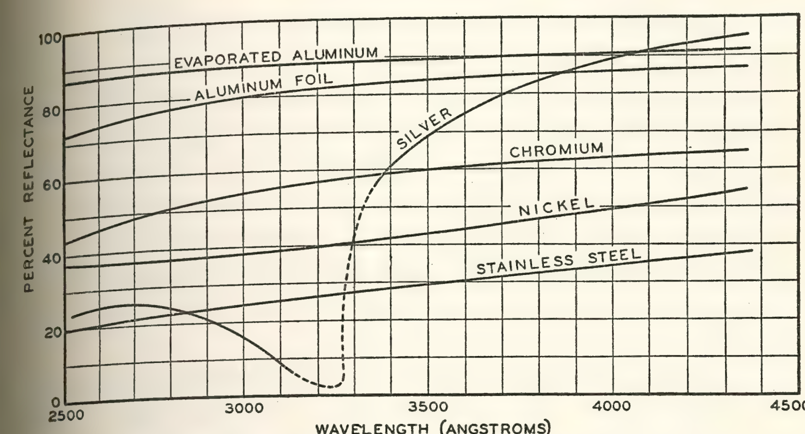


Fig. 117. Spectral reflectance of various metals.

the range used commercially. The brightened aluminum has a remarkably high reflection-factor. However, the reduction due to the anodic coating, although appreciable, still leaves aluminum as the most efficient metal surface available for controlling ultraviolet energy.

In Fig. 117 are presented the spectral reflectances of aluminum deposited by evaporation in a vacuum. This surface exhibits a remarkably high value throughout the ultraviolet region. Aluminum foil is quite practicable. The values for chromium, nickel and stainless steel are relatively low, but these are useful where aluminum is impracticable. Therefore, even their relatively low reflection-factors for energy of λ2537 are of value in certain uses of germicidal

energy. The dotted portion of the curve for silver is a region of partial transmission, as illustrated in Fig. 120. No reflectance measurements were made in this region due to lack of spectral energy from the source used. Therefore, this part of the curve is estimated from other measurements. Many other metals have been studied but none were efficient reflectors of ultraviolet energy.

In recent years aluminum paints have been improved in reflection-factor. In Table XLII the reflection-factors are presented for nine different aluminum paints for various important regions of the spectrum, including light or visible energy. We have found that intensive exposure to germicidal energy of λ2537 affects the reflection-factors of these aluminum paints. It is seen that the reflection-factors for energy of λ2537 and λ2967 are definitely increased. This increase is not as much or as definite for λ3650 and for light.

There is considerable interest in the reflection-factors of white pigments or powders for ultraviolet energy as well as for light or visible energy. Sometimes a high reflection-factor is desired, as in the case of measuring devices such as illustrated in Figs. 114 and 115. For this purpose magnesium oxide obtained by burning metallic magnesium is excellent. Its reflectance throughout the ultraviolet spectrum of practical interest is remarkably high. Many measurements for energy of λ2537 indicate that its reflectance is 93 percent which is greater than that of a pressed powder of magnesium oxide.

The author knows of no *absolute* standards of reflectance, and this includes smoked magnesium oxide. A. H. Taylor has found that a layer of smoked magnesium oxide approximately ⅛ inch thick, deposited on clear quartz, is not completely opaque to light from a tungsten-filament lamp. In order to achieve the maximum possible reflectance

TABLE XLII

Reflectance or Reflection-Factor of Nine Aluminum Paints Before and After Intensive Irradiation with Energy of λ2537

Percent							
λ2652		*λ2967*		*λ3650*		*Light*	
Before	*After*	*Before*	*After*	*Before*	*After*	*Before*	*After*
63	74	67	77	72	79	80	82
68	72	69	74	72	74	80	80
56	71	60	72	67	73	70	78
66	68	67	69	69	70	76	75
66	66	69	66	71	70	75	75
62	64	68	69	68	70	74	73
48	64	49	67	56	69	60	71
57	63	59	64	64	65	67	68
51	55	55	56	63	58	66	67

TABLE XLIII

Reflectance or Reflection-Factor of White Pigments and Other Materials

	Percent			
	λ2537	*λ2967*	*λ3650*	*Light*
Pressed zinc oxide	2.5	2.5	4	88
Barytes	65	70	77	86
Titanium oxide	6	6	31	94
Pressed magnesium oxide	77	86	87	93–95
Smoked magnesium oxide	93	93	94	95–97
Pressed calcium carbonate	78	83	86	96
White wall plaster	46	65	76	90
S.W. white Decotint paint	33	41	58	79
Kalsomine white water paint	12	20	40	70
Alabastine white water paint	10	14	45	78
White porcelain enamel	4.7	5.4	63	80
Flat black Egyptian lacquer	5	5	5	5
Lantern slide glass	4	4	4	4
Photographic paper (AZO, gloss)				
Exposed, black	6	6	6	6
Unexposed, white	24	43	72	81
White back	39	47	70	82
Samples of wallpaper				
Ivory	31	40	49	64
White	23	33	49	72
White	21	26	48	75
White	21	30	45	69
Pink figured	31	40	49	64
Ivory figured	26	35	50	75
Brownish figured	18	21	33	55

with *any* material, it is necessary to make the thickness such that it is opaque to the radiant energy under consideration. In the preparation of standard reflecting surfaces, it is our practice to compress a high grade of magnesium oxide powder into a metal ring under high pressure, making the surface over 1/16 inch below the edge of the ring, then burning metallic magnesium to smoke a layer of oxide approximately 1/16 inch thick on the surface. The compressed magnesium oxide has a reflectance only a little below that of the final smoked surface, so in effect we are substantially achieving "infinite thickness." Other materials can be painted with a white pigment before smoking with magnesium oxide. Titanium oxide is a white pigment of relatively high opacity or covering-power.

If one wishes a high reflectance for light and a low reflectance for ultraviolet energy, zinc oxide is a very satisfactory white pigment. This is an excellent pigment to use for the last coat on ceilings of rooms in which germicidal sources are used to irradiate the upper strata of air. If such a paint is used, relatively little of this germicidal energy will be reflected from the ceiling to the occupied area. Titanium oxide, whose opacity or covering-power is greater than zinc oxide, is also fairly satisfactory for this purpose. From Table XLIII it is seen that white wall plaster, cold-water paints and wallpapers may reflect considerable germicidal energy.

In general, if one wishes to make a paint that will reflect ultraviolet energy fairly efficiently, it is first necessary to choose a proper white pigment and use it in a cold-water paint. Generally such vehicles as oils and lacquers have high absorption-factors for ultraviolet energy, particularly for erythemal and germicidal energy.

White porcelain enamel and other vitrified surfaces absorb most of the incident ultraviolet energy just as glass

does. However, at least 4 percent of the incident energy is specularly reflected by these glazed surfaces. Common white papers have moderate reflection-factors throughout

TABLE XLIV

Reflectance or Reflection-Factor of Many Materials for Germicidal Energy of λ2537

	Percent
Duralumin	16
Tin plated steel	28
Brass	7
Chrome steel	39
Rhodium	38
Stellite	46
Speculum	30
Tungsten	18
Molybdenum	25
Celluloid	6
China clay	4
Medusa cement	11
Magnesium carbonate	75
Lithopone	5
Bleached wool	4
Bleached cotton	30
Linen	17
Pongee silk	6
White blotting paper	25
Brown wrapping paper	7
White baked enamel	9
Brown baked enamel	6
Casein vehicle	6
Zinc oxide casein paint	4
Zinc oxide in clear lacquer	5
Black lacquer paint	5
Several white oil paints	6–9
Several white water paints	10–35
Fluorescent-lamp phosphors	14–20

the ultraviolet region. The photographic papers are interesting in that the unexposed surface coated with the emulsion reflects ultraviolet energy fairly well, but the black surface, as a result of exposure and development, has a rather low reflectance. Many other materials have been tested but those in Table XLIII suffice to indicate the varia-

tions among materials. In general most materials have a higher absorption-factor than reflection-factor for erythemal and germicidal energy.

Owing to the new and expanding interest in germicidal energy of λ2537, we have determined the reflection-factors of many materials for this energy. Generally the reflection-factors increase as the wavelength of energy increases. Therefore, a high reflectance for λ2537 very generally indicates a higher reflectance for λ2967 and λ3650; but a low reflectance for λ2537 does not necessarily indicate a low reflectance for λ2967 and λ3650. The reflectances of many other materials for energy of λ2537 are presented in Table XLIV. Only one or two samples were involved in most cases, but the data should be fairly representative.

Wilcock and Soller [106] studied pigments and vehicles and various mixtures for their reflectance in the region of λ2800 to λ3200. Stutz [107] also measured the reflectances of pigments and paints for ultraviolet energy and Hulbert [108] studied various metals and alloys. These results have been presented elsewhere. They are not included here for the reason that the more recent data appear to be adequate.

TRANSMISSION OF ULTRAVIOLET ENERGY

In general most materials are not transparent to erythemal and germicidal energy of shorter wavelengths than λ3000. Notable exceptions are air, water and quartz. However, many special clear colorless glasses have been developed for transmitting the erythemal energy in sunlight and skylight and particularly for bulbs or tubes for artificial sources of ultraviolet energy. The development of glasses which efficiently transmit germicidal energy of λ2537 is of great practical importance. Previously, fused quartz had to be used. This is so costly and difficult to fabricate that the present germicidal sources are practicable

largely owing to the development of a glass substitute. Even the manufacture of this substitute requires great care in the purification of the materials. The content of iron, which commonly is responsible for the greenish color of ordinary glass, must be very low. The effect of iron oxide

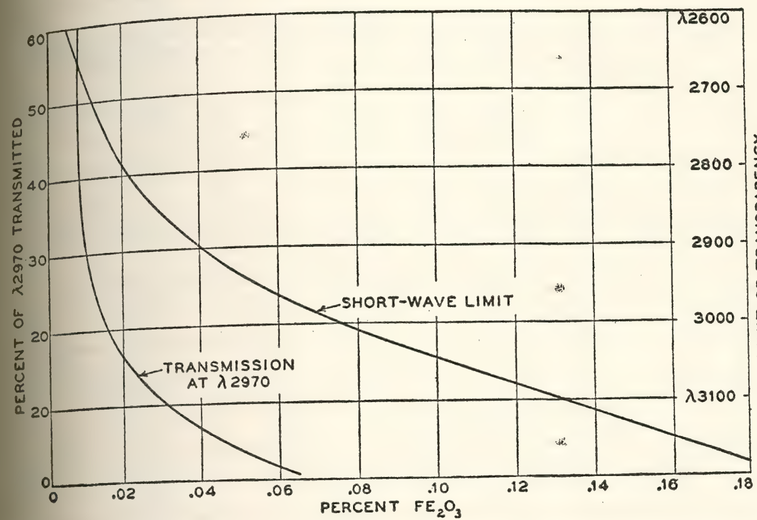


FIG. 118. Effect of iron oxide on the short-wave limit of transmission of glass.

on the short-wave limit of transmission of a glass is illustrated in Fig. 118 as determined by Starkie and Turner.[109] It is seen that only by eliminating or greatly reducing the iron content can a glass be made that will efficiently transmit energy of λ2537. We have also found that iron in minute quantities greatly affects the transmission-factor of water.

In Fig. 119 are shown the spectral transmission-factors of representative glasses that are available or used for artificial sources of ultraviolet energy. It is seen that any de-

sired short-wave cut-off can be obtained throughout the spectral region of practical interest. The steepness of the slope of the spectral transmission-curve near the short-wave cut-off is of great importance. The ideal slope is vertical,

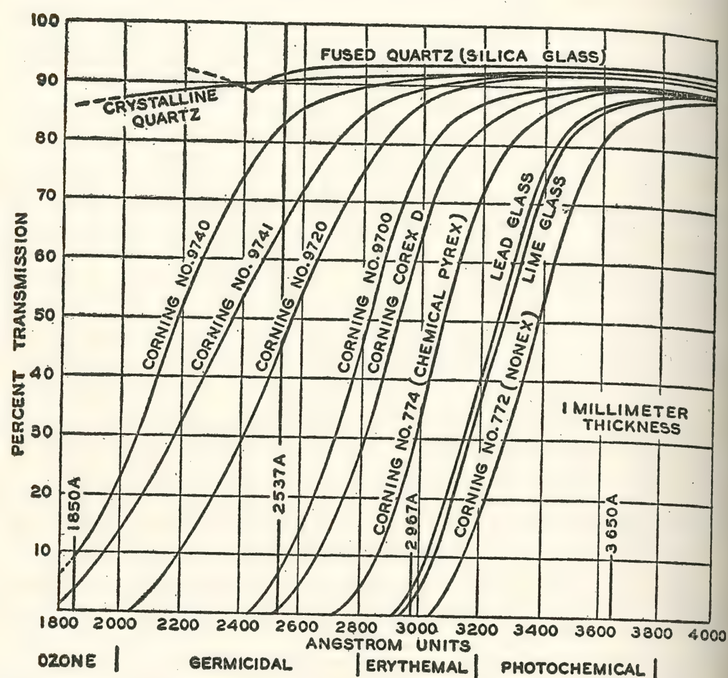


FIG. 119. Spectral transmission-factors of glasses used for sources of radiant energy.

but absorption bands do not have abrupt boundaries. There is a spectral region of transition from high to low transmission. For example, a glass for the germicidal sources should have a high transmission-factor at λ2537 such as 9740. Although this rapidly decreases with decreasing wavelengths, it transmits a few percent of the energy of λ1850 which produces ozone. If a glass such as 9741 is used,

the production of ozone is greatly reduced at a sacrifice of some of the transmission at λ2537. Naturally, a primary aim is to develop glasses with steep transmission-curves near the short-wave cut-off.

Variations in thickness of a given glass alter both its total and spectral transmission. For example, assume that glass of 9740, of 1 mm. thickness, transmits 84 percent at λ2537 and 10 percent at λ1850. If the thickness of the glass is doubled, the transmission-factor at λ2537 would be 84 percent of 84 percent or about 70 percent. The transmission-factor at λ1850 would be 10 percent of 10 percent or 1 percent. This illustrates how the thickness can be used to control the output of energy of desirable and undesirable wavelengths. Concentration of a given ingredient of a clear glass can be utilized in a similar manner. This exponential law applies only to a homogeneous transparent non-diffusing glass or other medium.

Some glasses are somewhat unstable and, under the influence of ultraviolet energy, their transmission-factors are altered. They are said to solarize. Generally, the short-wave cut-off moves somewhat to a longer wavelength. In some cases they will return to their original spectral transmission on heating to a sufficiently high temperature. Some glasses which solarize at ordinary temperatures do not do so at higher temperatures. Such a glass, if it is rather hot when in use, as in the case of some artificial sources of ultraviolet energy, does not solarize significantly. The glass tube of germicidal sources of the low-pressure mercury-vapor type is merely warm when in operation. Therefore, it must be a stable glass, for it cannot depend upon being desolarized by a high temperature.

Very useful glasses are available for transmitting ultraviolet energy between λ2500 and λ4000 without transmitting appreciably in the visible spectrum. They have the

appearance of very dense purplish glasses. They are used as filters for various sources which emit long-wave ultraviolet energy for the primary purpose of exciting fluorescent materials. When used with sources that emit considerable erythemal flux, this socalled "black light" produces erythema of the skin. When used with sources emitting no appreciable energy shorter than λ3100, reasonable exposures do not affect the eyes or skin adversely.

The spectral transmission-factors of a series of 7 useful glass filters are illustrated in Fig. 29. Another useful series of 8 glass filters is illustrated in Fig. 35. These indicate how readily a series can be found which is very useful in various researches and tests.

Various substitutes for glass have been used. Loosely woven cotton cloth impregnated with paraffin transmits some energy well into the middle ultraviolet region. A thin layer of paraffin transmits about 20 percent of the energy longer than λ2600. However, the cotton fibers permit only a small percentage of the incident ultraviolet energy to pass through. Such cloth has some value when and where sunlight or skylight is of high intensity, but it is of doubtful value in winter.

Various thin plastic films are being used as substitutes for glass chiefly for their greater transparency to erythemal energy. They differ considerably in their transmission of ultraviolet energy. Some thin films transmit appreciably in the region of λ2500. Nine different transparent plastic films, about 0.001 in. in thickness, were found to have transmittances of 12 to 76 percent at λ2967. On increasing the thickness of such films the transmittance of erythemal energy rapidly decreases. These materials generally decrease in transmittance by prolonged exposure to energy less than λ3000.

In Table XLVI are presented the approximate short-wave limits of various materials.

Certain properties of pyrex glass make it useful in various practical ways in connection with radiant energy. It is available in various thicknesses with smooth or pebbled surfaces. The transmission-factors of several specimens of thick pressed pyrex panels for energy of various wave-

TABLE XLV

Transmission-Factors of Pyrex Glass, Expressed in Percent, for Ultraviolet Energy of Four Wavelengths

	λ3022	*λ3130*	*λ3342*	*λ3650*
Sheet, 3 mm. thick	21	47	79	89
Sheet, 4.85 mm. thick	7	30	69	89
Pebbled sheet, 3 mm. thick	23	44	73	82
Pressed sight, 5.8 mm. thick	7	29	72	89

lengths are presented in Table XLV. It is seen that pyrex, in the thicknesses indicated, transmits some erythemally-effective ultraviolet energy. Their transmission-factors of erythemal flux emitted by the water-cooled H-6 lamp in quartz are about 12 percent for the specimens 3 mm. thick and about 5 percent for the other two specimens. Such a glass can be used for installations of artificial sunlight if the sources emit considerable energy in the region of λ2950 to λ3200. The two specimens 3 mm. thick transmit some energy of λ2967, but the two thicker specimens are nearly opaque to energy shorter than λ3000.

In Fig. 120 are shown the spectral transmission-factors of films of silver deposited on quartz plates. *A* is for a thin film and *B* for a thicker film. *C* is the result obtained through both films. It is seen that thin silver films are quite transparent in the region of λ3400 to λ3500. This property of silver has some interesting applications. It provides a means of obtaining long-wave ultraviolet energy with little

or no light. In this connection it is interesting to examine the spectral reflection-factors of silver in Fig. 117.

The slightly tinted glasses that are used to some extent for eyeglasses generally reduce the extent of the spectrum of daylight somewhat. Their transmission-factors for energy in the region of λ3000 to λ3500 are generally less than

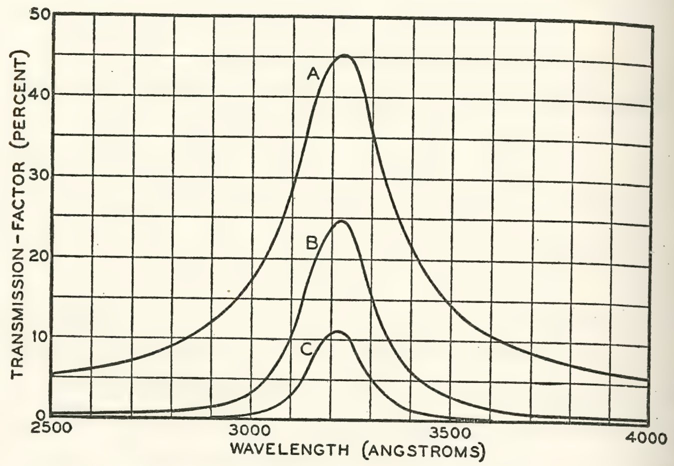


FIG. 120. Spectral transmission-factors of silver films deposited on quartz plates. *A*, thin film; *B*, thicker film; *C*, both plates.

that for ordinary glass. However, clear flint or the glass commonly used for the element of higher refractive index in bifocal lenses is fairly opaque to energy less than λ3300. A lens of ordinary colorless glass may transmit 40 percent of the energy in midday summer sunlight below λ3150. One of the most popular tinted lenses sold for eyeglasses transmits from 8 to 15 percent of this energy in its lighter tints. Clear flint glass is opaque to this energy. Of the energy shorter than λ3500 in summer sunlight, ordinary colorless eyeglasses transmit about 75 percent and this popular tinted eyeglass transmits about 50 percent. These

results are merely approximate, for they depend upon the thickness of the glass, its composition and depth of tint. They generally reduce the short-wave energy in daylight

TABLE XLVI

Approximate Short-Wave Limits of Transparency of Various Materials

Materials of various thicknesses	
Window glass, 50 samples, 1 to 7 mm.	λ3059 to 3200
Optical lenses, 1 to 10 mm.	3200 to 3500
Celluloid, 0.2 mm.	2929
Cellophane, thin	2600
Photographic film, 0.1 mm.	2562
Paraffin, 0.2 mm.	2185
Mica, 0.1 mm.	2929
Fused borax, 3 to 6 mm.	2327 to 2628
Phosphoric acid, 3 to 6 mm.	2750 to 2874
Canada balsam, 0.1 mm.	3300
Gelatin, 0.1 mm.	2000
Optical glasses, 2 mm. thick	
Light crown	2950
Extra light flint	2980
Medium crown	3000
Light flint	3050
Medium flint	3150
Extra dense flint	3350
Materials 1 mm. thick	
Fluorite	1250
Quartz crystal	1600
Potassium chloride	1610
Gypsum	1700
Boric oxide	1700
Rock salt	1750
Sodium and potash alum	1750
Water	1729
Iceland spar	2000

which reaches the eye. The need for them and what they accomplish are other matters. The author likes them from an esthetic viewpoint. A slight and proper tint renders the eyeglasses less conspicuous and blends with the complexion to a considerable degree.

The spectral transmission-factors of liquids are of interest in various specific cases. Those of water and other

liquids that can or might be disinfected or sterilized by germicidal energy are of particular interest especially in the region of λ2537. The transmission-factors of various clear waters have been presented and discussed extensively in Chapter IX. The practicability of disinfecting water with germicidal energy on fairly large scales is fairly well established. Fortunately the absorption-coefficients of various waters are reasonably low, although waters vary considerably in their transmittance of energy of λ2537. Iron in solution is commonly responsible for much of the absorption of λ2537 by water. The transmission-factor of distilled water is so great that its depth must be increased to 115 inches before 90 percent of the incident energy of λ2537 is absorbed. When one part of ferric chloride is added to one million parts of the distilled water, a depth of only 4 inches absorbs about 90 percent of the incident energy of λ2537.

The absorption-factors of some representative clear waters are presented in Table XLVII. It is easy to visualize these by means of the depths which absorb 90 percent of the incident energy of λ2537. Waters from the public supply system of 20 cities were found to have absorption-coefficients from 0.47 to 0.07 per inch. This means that the depths which absorb 90 percent of the incident germicidal energy vary from about 5 to 35 inches. Naturally, the design of adequate and efficient systems of germicidal energy for disinfecting water and other liquids is determined by the absorption-coefficient in each case. Germicidal energy of sufficient intensity must reach the micro-organisms for a sufficient period of time if they are to be killed.

It is seen in Table XLVII that beverages such as beers and wines have high absorption-coefficients. This means that thicknesses of a small fraction of an inch absorb 90 percent of the incident energy. This does not mean that they cannot be sterilized by means of germicidal energy.

TABLE XLVII

Absorption-Coefficients *a* (per Inch) of Various Liquids and the Depths in Inches Which Absorb 90 Percent of the Incident Germicidal Energy of λ2537

	a	*Inches*
Clear waters		
Distilled	0.02	115
Swimming pool	0.08	28
Drilled well	0.14	16
Fish pool	0.18	13
Lake Erie	0.21	11
Concrete cistern	0.75	3
Public supply, 20 cities	0.47 to 0.07	5 to 35
Atlantic Ocean	0.23	10
Beverages and foods		
Wine, red port	67	0.03
Wine, sherry	23	0.10
Wine, muscatel	17	0.13
Wine, blackberry	70	0.03
Beer, 3 brands	41	0.055
Beer, 3 brands	38	0.06
Coca-Cola, bottled	77	0.03
Apple juice, bottled	42	0.05
Sugar syrup, brown	95	0.02
Sugar syrup, colorless	6.2	0.38
Milk, raw whole	730	0.003
Vinegar, brown	16.3	0.14
Vinegar, brown	12.8	0.18
Vinegar, colorless	3.9	0.60
Egg white	11	0.2
Miscellaneous liquids		
Boric acid in distilled water	0.05	46
Plant nutrient	0.83	2.75
Methyl alcohol	0.59	3.9
Ether, USP	0.52	4.4
Ether, USP	1.29	1.75
Isopropyl acetate	3.6	0.64
Ethyl acetate	9.4	0.24
Butyl acetate	30	0.08
Butyl alcohol	13	0.17
Ethyl alcohol, denatured	15	0.15
Isopropanol	2.3	1.0
Cellosolve acetate	7.1	0.32
Ethyl lactate	25	0.09
Nitropropane	8.1	0.28
Carbitol solvent	7.6	0.30
Methyl ethyl ketone		less than 0.05
Diacetone		less than 0.05
Benzene		less than 0.05
Amyl acetate		less than 0.05
Solvesso		less than 0.05
Beetle lacquer		less than 0.05

Such liquids can be flowed in thin layers over riffles under a bank of germicidal sources. They might be flowed slowly through a container in which the germicidal sources are immersed in the liquid. These possibilities are illustrated in Chapter XVI.

Sugar syrup has a very high absorption-coefficient. Possibly this accounts for some of the absorption by Coca-Cola and apple juice. Colorless vinegar has a lower absorption-coefficient than brown vinegar due chiefly to the absence of coloring matter. Experiments have shown that the organisms which produce the "mother" can be killed by energy of $\lambda 2537$. Some efforts toward partially disinfecting milk were made years ago with the quartz mercury-arc. As seen in Table XLVII, a very thin film of milk absorbs 90 percent of the incident germicidal energy.

Many other liquids have been examined for their transmission of $\lambda 2537$. Some of these have been included in Table XLVII to show that most liquids have high absorption-coefficients for germicidal energy.

A film of raw whole milk, 0.15 mm. or 0.006 inch thick, was found to transmit only 1.3 percent of the incident germicidal energy of $\lambda 2537$. It transmits 0.9 percent at $\lambda 2804$, 8.6 percent at $\lambda 3130$ and 11 percent at $\lambda 3650$.

In artificially infecting water with B. coli in order to study the rate of killing with germicidal energy, it is desirable to introduce a slight amount of nutrient. Naturally the effect of this on the transmission of the water is of interest. Using Levine's Eosin Methylene Blue Agar in distilled water we found that, with a concentration of 4 mg. per liter of water, a 12-inch depth of the solution transmitted 40 percent of the incident energy of $\lambda 2537$. With a concentration of 8 mg. per liter of water, 90 percent of the incident energy of $\lambda 2537$ was absorbed by a 15-inch depth of the solution. With a concentration of 32 mg. per liter of water

a 6-inch depth of the solution absorbed about 90 percent of the incident energy. The effect of the nutrient upon the transmission of germicidal energy by the water is insignificant at low concentrations which are generally adequate for experimental work on the disinfection of water which is artificially infected with B. coli. If for any reason higher concentrations are used, such as those mentioned in this paragraph, their effect in significantly increasing the absorption of the water should be taken into account.

Measurement of Ultraviolet Energy

MEASUREMENTS, and coordinations of them among themselves, and with various effects, provide the basis of knowledge. They are essential in establishing a scientific foundation for technological practices. They are also essential in actual practice. For laboratory purposes, the devices and techniques may be as complicated and cumbersome as necessary to meet the requirements of sensitivity and accuracy. For field work, simplicity and portability are desirable characteristics. In the course of decades of laboratory researches many complex devices and techniques are developed and some of these have extensive practical applications. In the present discussion some of these are briefly discussed, and where space is not given to details, the reader is referred to the original papers in which they are described. This discussion does not aim to be a complete review of all the measuring devices and techniques. Instead, its purpose is to present adequate glimpses so that the reader will have a fair understanding of the possibilities of measurements and of the availability of devices suitable for major uses of ultraviolet energy.

If one is satisfied merely to measure the radiant energy of various wavelengths, any energy-measuring device or method suitable for the purpose may be used. However, in the use of ultraviolet energy we are inevitably interested in various effects. In the major use of light for seeing, we do not merely measure visible radiant energy. We evaluate it in accordance with its ability to produce luminosity or the sensation of brightness. In this case the spectral sensitivity of the visual sense, or the "spectral luminosity curve" of

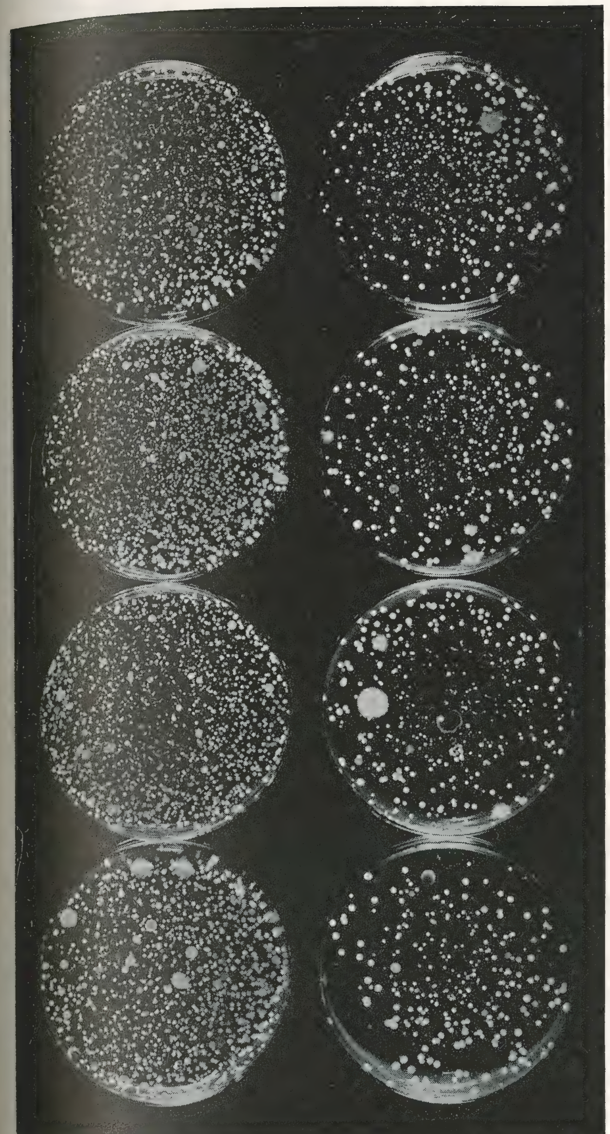


PLATE XV. In a poultry house one 30-watt germicidal source was installed for each 300 sq. ft. of floor area. Petri dishes were identically exposed in a DE air-sampler when the germicidal sources were operating (lower row) and when they were not (upper row). The difference in the concentrations of air-borne micro-organisms is apparent.

the average normal human eye is available as illustrated in Fig. 33.

In the use of ultraviolet energy, various effects are of interest but, with the exception of the spectral germicidal effectiveness and spectral erythemal effectiveness of energy of various wavelengths, only vague spectral data are available. For example, the spectral range of antirachitic effectiveness is roughly known, but the effectiveness of energy of various wavelengths is not established as it is for erythemal effectiveness (Fig. 30) and germicidal effectiveness (Fig. 34). Some of the other effects of ultraviolet energy are indicated in Figs. 26 and 38. Practical applications of the major uses of ultraviolet energy need not await the development of desirable spectral data pertaining to other major effects of radiant energy. In all fields practice proceeds while science advances and refines knowledge.

Germicidal flux from low-pressure mercury-vapor sources is concentrated at $\lambda 2537$, and it is easy to isolate. This eases the difficulty of making relatively simple devices for measuring it. This energy, being concentrated in a narrow spectral range which fortunately is practically coincident with the maximal germicidal effectiveness of ultraviolet energy, makes it unnecessary to weight energy of various wavelengths for there is none. On the other hand, if the quartz mercury-arc of higher vapor pressure is used, the energy of various wavelengths must be weighted in accordance with the germicidal effectiveness of each wavelength as illustrated in Fig. 34.

The antirachitic effectiveness of ultraviolet energy is known to be largely confined to wavelengths shorter than $\lambda 3100$. In the absence of established relative effectiveness of energy of various wavelengths, it is impossible to accurately weight the heterogeneous energy emitted by a source. In parts of the ultraviolet spectrum the antirachitic and ery-

themal effectiveness are roughly coincident. For this and other reasons erythemal flux and effectiveness are of practical interest and value.

One may similarly lament the absence of data pertaining to various beneficial and useful effects of ultraviolet energy. However, with a general view combined with the available knowledge of details, practice need not mark time nor progress blindly. Careful practice, accompanied by measurements, aids science while science is directing and refining practice.

In various preceding chapters measuring devices and techniques have been discussed and many measurements have been presented. These need not be repeated here. For example, in Chapter VII devices for sampling air for its content of micro-organisms have been adequately discussed and efficient portable devices have been described. In Chapter IX a practical device for measuring the transmission and absorption of germicidal energy by water and other fairly transparent liquids is illustrated and the results are presented. In Chapter XIV devices for measuring the reflection and transmission of various media are illustrated and discussed.

GERMICIDAL ENERGY OF λ2537

The measurement of germicidal energy from low-pressure mercury-vapor sources is somewhat simplified by the fact that about 95 percent of all the ultraviolet energy is emitted by these sources in a narrow band at λ2537. About 98 percent of this ultraviolet energy is absorbed by a sheet of ordinary glass. Therefore, by the use of clear quartz and clear glass the energy of λ2537 can be isolated. This is a simple and practical expedient which is very useful in connection with the fluorescence of zinc silicate whose relative sensitivity or fluorescence due to ultraviolet energy

of various wavelengths is illustrated in Fig. 121. It is seen that the fluorescence is entirely due to ultraviolet energy which is not transmitted by ordinary glass and fortunately is a maximum for energy in the region of λ2537.

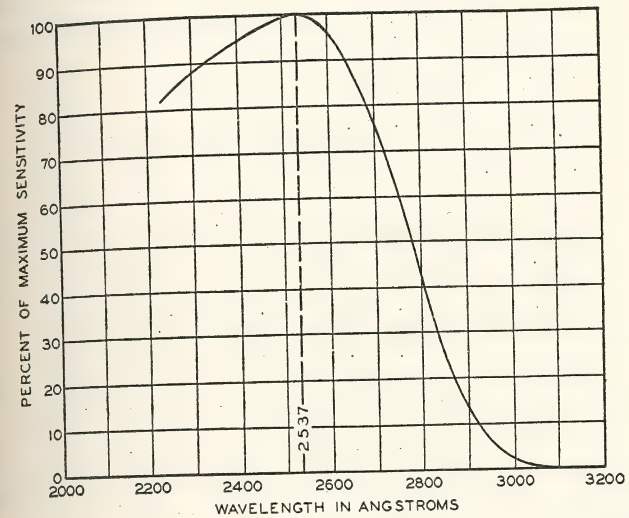


Fig. 121. The relative sensitivity or fluorescent brightness of zinc silicate for equal amounts of incident energy of various wavelengths.

Combining these facts, Luckiesh and Taylor [110] produced a simple attachment for a G.E. Light Meter illustrated in Fig. 122. It consists of a layer of zinc silicate on a piece of ordinary clear glass and covered with a piece of clear quartz. When exposed to energy of λ2537 with the quartz plate uppermost, the phosphor fluoresces and the light meter indicates Q footcandles. A part of this deflection is due to the fluorescence of the phosphor and the remainder is due to light from the germicidal source which is transmitted by the entire device. When the device is turned over so that the glass is uppermost, the germicidal energy does not reach the phosphor and the light meter reads G

footcandles. $Q - G$ represents the deflection due to the excitation of the phosphor by the energy of λ2537. Each footcandle deflection of $Q - G$ is produced by about 40 microwatts per sq. cm. of energy of λ2537. Each device is calibrated and its individual constant is supplied. Thus we have a very simple device which is adequate for comparing

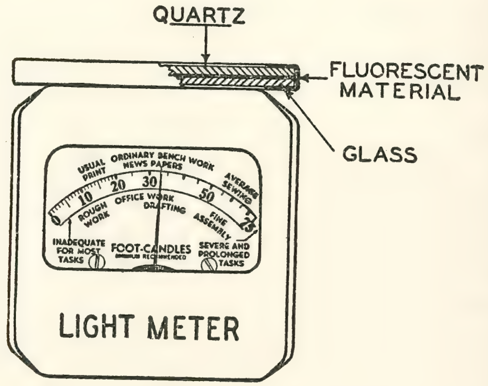


Fig. 122. Attachment for General Electric Light Meter for the measurement of germicidal energy.

different germicidal sources of the same wattage or for determining the depreciation of a given source. When this attachment is used with an ordinary G.E. Light Meter it is quite useful at distances up to 2 feet from a 15-watt germicidal source. When used with a high-sensitivity G.E. Light Meter, it is useful at distances up to 4 feet.

Taylor[111] has compensated for the non-fluorescent brightness of the phosphor by connecting two light-sensitive cells in series, one being covered with quartz and the other with glass. Both covers are coated with zinc silicate on their inner side. This meter, illustrated in Fig. 123, is connected to a portable galvanometer so as to measure the difference in current generated by the two cells. By proper

Fig. 123. Compensated double light-sensitive cells used with a sensitive portable galvanometer. The deflections are directly proportional to the intensity of energy of λ2537.

selection of the two light-sensitive cells and by proper thickness of the phosphor coating, it is possible to balance out the response due to energy other than λ2537. The sensitivity of this device is about one microampere for an

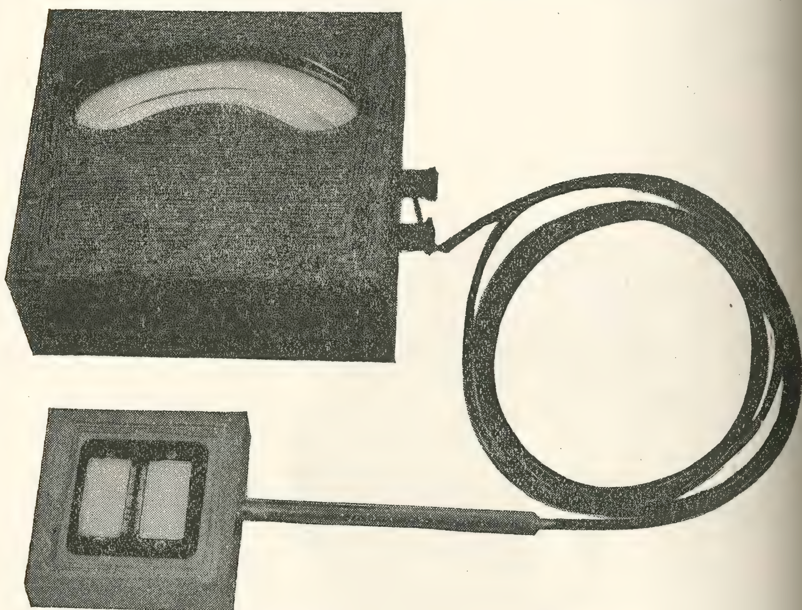


FIG. 124. Compensated double light-sensitive cells connected to a microammeter. The cells are covered with a water-tight quartz plate for use under water.

intensity of 10 microwatts per sq. cm. of energy of λ2537. This meter is useful at distances up to 6 feet from a 15-watt germicidal source when used with a portable microammeter and up to 25 feet when used with a sensitive portable galvanometer. The two cells have also been covered with a quartz water-tight cover to measure intensities of germicidal energy at various depths of water.[112] Such a device connected to a portable microammeter is illustrated in Fig. 124.

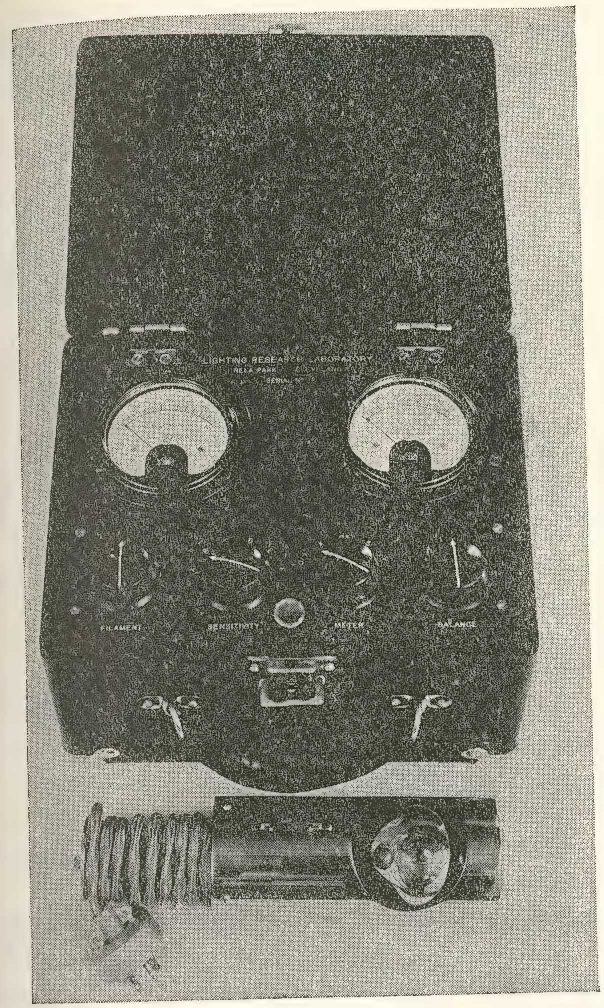


FIG. 125. An indicating ultraviolet meter consisting of a cadmium-magnesium phototube and amplifier.

A decade ago Koller and Taylor [113] were interested in developing a phototube applicable to the measurement of erythemal energy in the spectral region of practical inter-

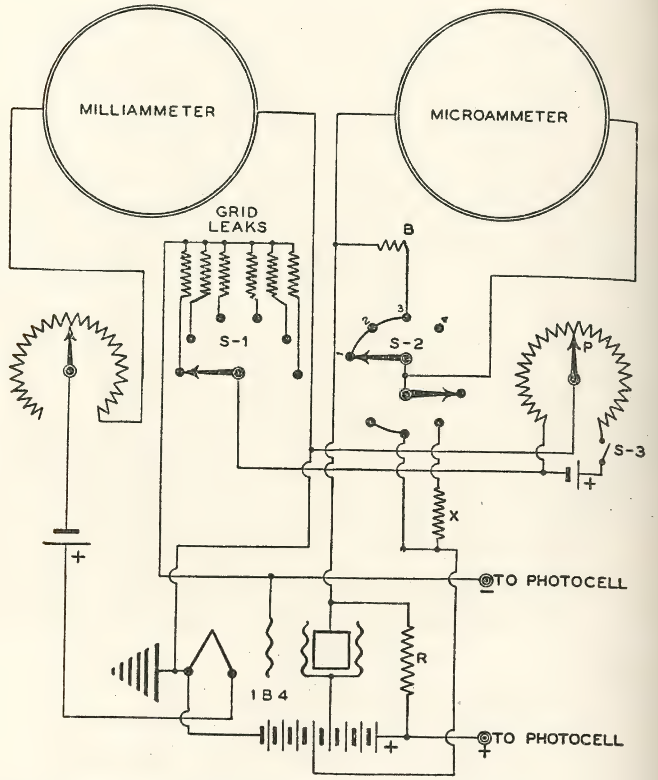


Fig. 126. The wiring diagram for the amplifier illustrated in Fig. 125.

est. As a result, they produced a phototube having a cathode of cadmium-magnesium alloy in a bulb of thin Corex D glass. Individual tubes vary in spectral sensitivity, but in general they are not sensitive to energy of wavelengths longer than about λ3200. They can be used throughout the erythemal region of the ultraviolet spectrum and various

applications have been described by Luckiesh and Taylor.[114]

With the amplifier illustrated in Fig. 125, this phototube has proved very satisfactory for the measurement of energy of λ2537, for not more than one percent of its response is due to energy of other wavelengths. The low sensitivity of this phototube to radiant energy from common light-sources makes it possible to measure germicidal energy in an illuminated room. If daylight enters the room through ordinary window glass, this device can be used in daylight. This meter weighs 12 pounds and is useful at distances up to 150 feet from a 15-watt germicidal source.

In Fig. 126 is reproduced the wiring diagram of the amplifier illustrated in Fig. 125. The sensitivity is varied by selecting the proper grid-leak resistor by means of the switch *S-1*. These resistors range from 100,000 ohms to 500 megohms and by using a half-scale setting of the microammeter, the sensitivity can be varied over a range of about 1 to 10,000. The switch *S-2* connects the microammeter into the circuit. By means of switch *S-3* and the potentiometer *P*, the plate current of the 1B4 vacuum tube is adjusted for zero reading of the microammeter. This is done when the photocell is not exposed to ultraviolet energy. When the photocell is exposed, its current is amplified by the vacuum tube and the deflection of the microammeter is proportional to the intensity of the ultraviolet energy incident on the photocell. The milliammeter and rheostat are used in adjusting the current through the filament of the vacuum tube 1B4.

When germicidal energy is used to disinfect the upper stratum of air in an occupied room, some energy is reflected by the ceiling and upper walls. For 8-hour occupancy a limit of 0.5 microwatt per sq. cm. has been tentatively established for the intensity of germicidal energy on the occupants. A simple device for measuring these low inten-

sities, developed by A. H. Taylor,[115] is illustrated in Fig. 127. An old-style footcandle meter was used as a basis, but the principle can be used in other ways. The upper photometric surface is coated with a suitable phosphor such as

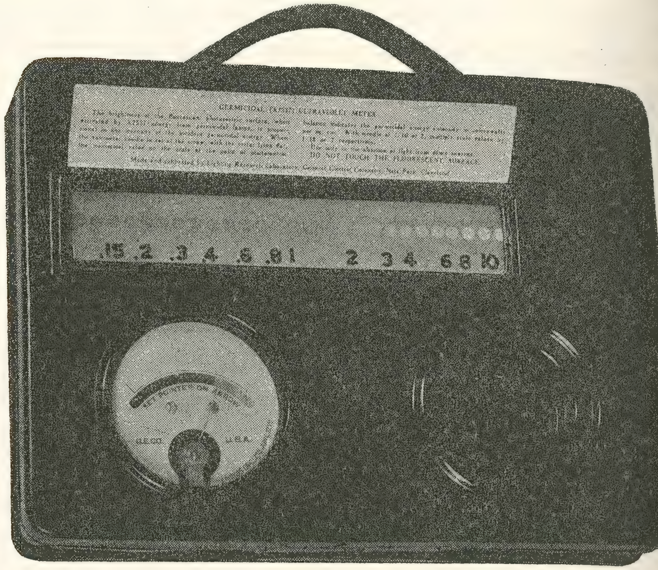


Fig. 127. A simple device for measuring intensities of germicidal energy from 0.2 to 20 microwatts per sq. cm.

zinc silicate. When this is excited in the absence of other light-sources, the brightness of the fluorescent surface is due to the energy of λ2537 plus a very low brightness due to the light from the germicidal sources. The non-fluorescent circular spots derive their brightness from the small filament lamp at one end of the trough underneath the photometric surface. The color-difference is minimized by means of a tinted filter. The numerals on the scale could be of a different color of fluorescence, but in any case they must be large enough to be read at low brightness-levels.

This meter must be used in the absence of light from other sources. The surface of the phosphor is quite diffusing so that it integrates fairly well the incident germicidal energy which arrives from various directions.

BIOLOGICALLY-BENEFICIAL ENERGY

It has been repeatedly emphasized that devices and methods of weighting ultraviolet energy according to its erythemal effectiveness usually have as their real objective the determination of antirachitic or, more broadly, biological effectiveness. Measurements of erythemal flux and intensities at least provide a basis of comparison and practice. This is particularly true of the ultraviolet energy in daylight which is absorbed by ordinary window glass. Thus considerable attention has been given to the spectral region from λ2800 to λ3200. Theoretically, the solution of the problem is rather simple, for it is only necessary to obtain a receiver which weights ultraviolet energy in this region according to the spectral erythemal effectiveness illustrated in Figs. 28 and 30. Practically, the difficulty lies in finding or developing a receiver of this basic spectral characteristic. It may be a phototube or other light-sensitive cell, a fluorescent material or a chemical reaction, a filter with a suitable spectral-transmission characteristic, or a combination of any of these.

If the ultraviolet energy in the region of λ2800 to λ3200 is weighted so as to determine the erythemal flux, there is little doubt that this is approximately related to antirachitic flux or, more generally, biologically-beneficial flux. From the scanty available data, it appears that certain biological benefits are obtained from ultraviolet energy shorter than λ2800. It is also quite likely that the effectiveness of energy of these shorter wavelengths differs con-

siderably, depending upon the effect. This is illustrated in Fig. 26. Therefore, we arrive at the conclusion that erythemal flux is a rough measure of the biological benefits of

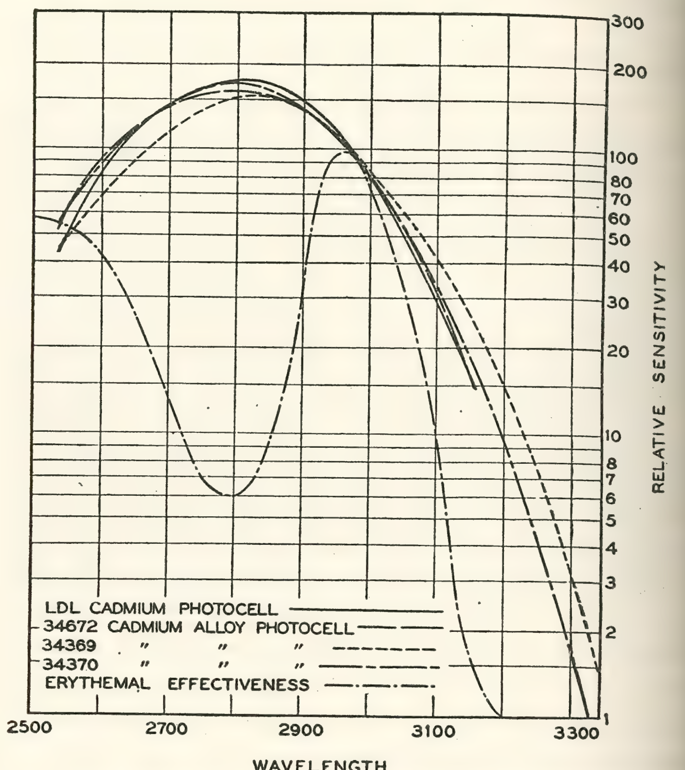


FIG. 128. Relative spectral sensitivity of a cadmium and three cadmium alloy photocells compared with the erythemal effectiveness of energy particularly from λ2950 to λ3200.

ultraviolet energy in outdoor sunlight and skylight and in artificial sunlight to which we can be safely exposed for any desired period of time. There is less certainty about the relationship of erythemal flux to biologically-beneficial flux from λ2800 to λ2500, but in the absence of a better

means, we are forced to use this expedient. However, it does provide guidance in the determination of dosages that are safe for human eyes and skin.

In the search for a suitable receiver, various devices and methods have been developed. Most of these are obviously crude appraisers of the ultraviolet energy of interest. These were summarized elsewhere [1] in 1930 so that in this chapter the discussion is confined chiefly to more recent developments. Most of these are the products of the author and his colleagues who have worked continuously in this field. Taylor [116] investigated various phototubes, fluorescent materials and filters in a comprehensive study and compared various devices and methods.

Several investigators [117] had found that cadmium phototubes were promising appraisers of erythemal flux. Taylor continued this work with the result that he developed various practical instruments and with Kerr [118] provided a suitable amplifier which was the forerunner of several others.[114] In Figs. 125 and 126 is illustrated a very sensitive indicating meter which is one of several types which resulted from this work.

In Fig. 128 are plotted the spectral sensitivities of typical cadmium and cadmium-magnesium photocells during the early progress of this development. They are compared with spectral erythemal effectiveness on average untanned skin. It is seen that their spectral sensitivity is fairly satisfactory in the region from λ2900 to λ3200, and their continuing high sensitivity from λ2900 to λ2500 probably provides a better measure of biological benefit than erythemal effect does.

It is interesting to compare the spectral sensitivity of various devices and materials, in Fig. 129, which have been proposed or used for appraising erythemal flux. The fluorescence of uranium glass *C* is entirely unsuitable even with

a red-purple filter which absorbs most of the visible energy. The blue-fluorescing glass B was first mentioned by H. P. Gage and was studied extensively by Taylor and Holladay [119] along with various other devices and materials,

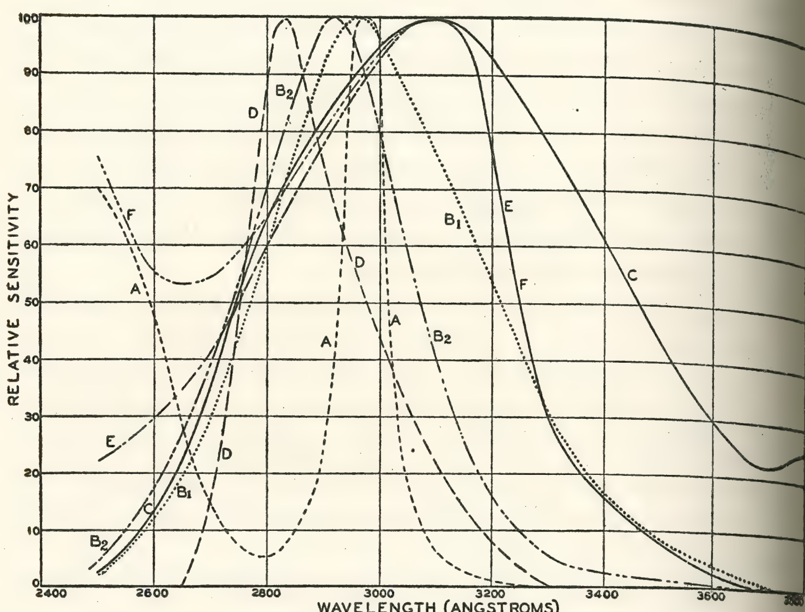


FIG. 129. Relative spectral sensitivity of various materials to ultraviolet energy. *A*, erythemal effectiveness; B_1, blue-fluorescing glass with red-purple Corex A filter; B_2, blue-fluorescing glass with and without 1.5 mm. pyrex filter; *C*, uranium glass with red-purple Corex A filter; *D*, cadmium photocell with Uviol filter; *E*, zinc sulphide; *F*, lithopone.

including photochemical reactions, fluorescence, phosphorescence, photocells, and non-selective devices with appropriate filters. In Fig. 130 is illustrated an indicator of erythemal flux in which a blue-fluorescing glass is covered with a red-purple ultraviolet-transmitting filter. Modifications of this have been devised for quantitative measurements.

Pfund [120] found that bromine vapor filters out visible and long-wave ultraviolet energy and has a maximum transmittance in the region of λ3100. He filled a thin glass bulb with this gas and placed it in front of a uranium glass which fluoresces a yellow-green. The combination of the

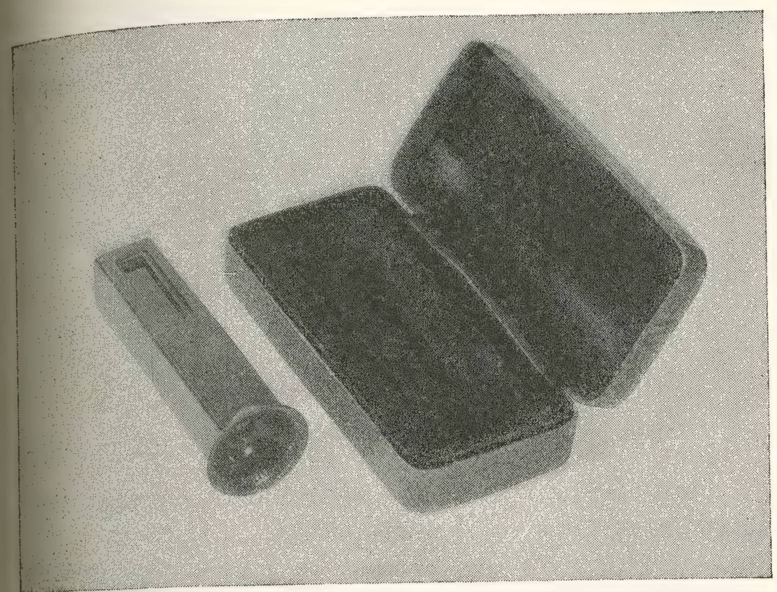


FIG. 130. An indicator of erythemal energy using blue-fluorescing glass covered with a red-purple ultraviolet-transmitting Corex A filter.

spectral transmission of the thin glass bulb and the bromine vapor with the spectral response of uranium glass produced a device with a maximum sensitivity close to λ2967. The sensitivity drops rapidly on both sides of this maximum. The data pertaining to the various elements are presented elsewhere.[1]

Rentschler [121] developed a method which integrates the output of ultraviolet energy over any desired period. The electrical circuit is illustrated in Fig. 131. The battery *B*

charges the condenser C at a rate determined by the photoelectric current produced in the uranium photocell P when ultraviolet energy is incident upon its cathode. The rate of charging or discharging of the condenser has usually been measured by means of an electroscope or electrometer. Rentschler introduced a specially designed glow relay tube G in place of these devices. It has for a cathode an

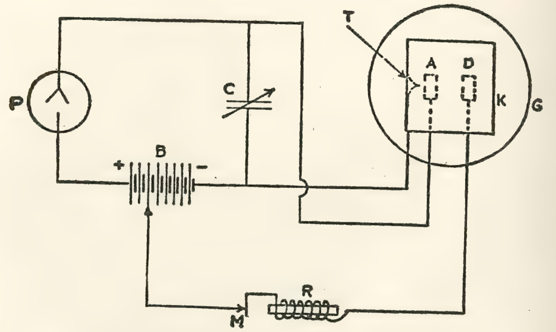


Fig. 131. Diagram of electrical circuit of Rentschler's ultraviolet meter.

iron metal cylinder K. There are two anodes. A is a starting anode, preferably of thorium metal, and D is the main anode. A small iron or nickel wire T is welded to the cathode so that a short gap exists between it and the starting anode A. The main anode D is connected to B through a relay R. When ultraviolet energy falls on the cathode of the photocell P, the photoelectric current charges the condenser C and eventually a discharge takes place between K and A, the cathode resistance of the glow tube is broken down and a current flows between the main anode D and the cathode. This operates a relay, registers the count, and opens the main circuit M. Simultaneously the condenser is discharged and the cycle begins again. The intensity of ultraviolet energy capable of producing photoelectric current in P is proportional to the rate at which the counter

registers and the total quantity of effective radiant energy is proportional to the total number of discharges.

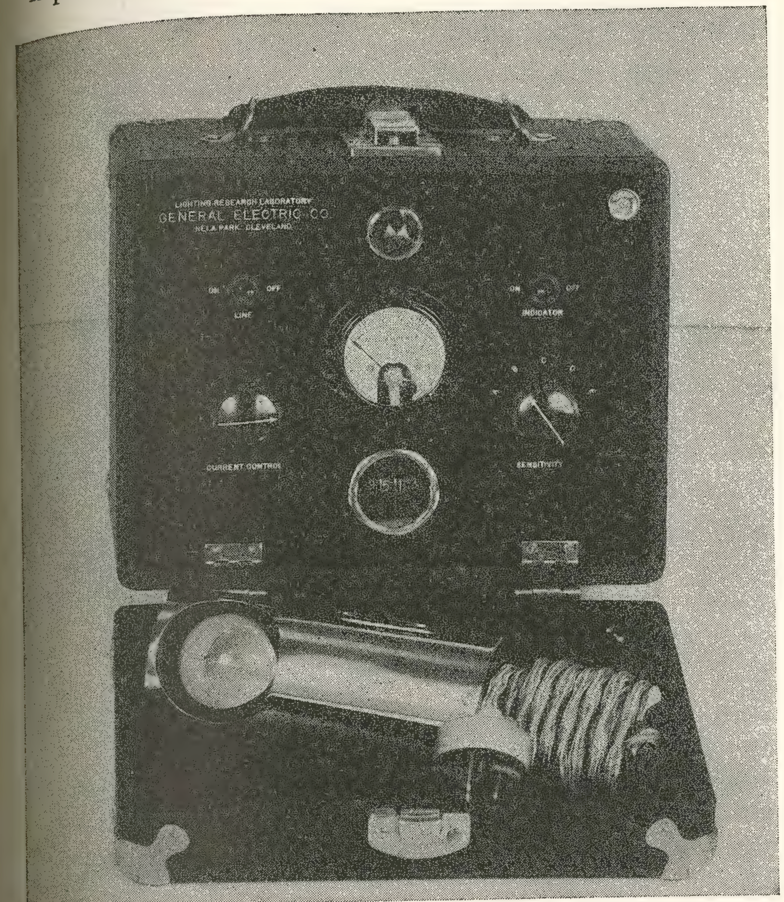


Fig. 132. A portable integrating ultraviolet meter of high sensitivity.

Obviously, the accuracy with which the ultraviolet energy is weighted erythemally depends upon the spectral sensitivity of the uranium photocell. According to Rentschler, it does not respond to energy longer than λ3200. By

using an envelope of quartz or of a suitable ultraviolet-transmitting glass, this cell and the entire device will make a continuous record of the ultraviolet energy between λ3200 and any desired shorter wavelength.

Taylor [122] devised adaptations of this principle and by

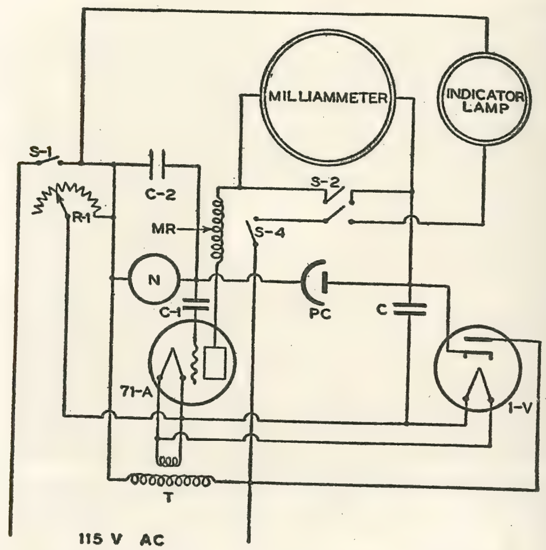


Fig. 133. Diagram of the electrical circuit of the integrating ultraviolet meter illustrated in Fig. 132.

using cadmium and cadmium alloy photocells produced several portable integrating meters which appraise ultraviolet energy in terms of biologically-effective flux.[114] One of these, with the phototube lying on the cover, is illustrated in Fig. 132. The registering counter is shown in the middle near the bottom of the control-board. The indicator lights up at each discharge of the condenser. One of these devices was used to obtain a continuous six-year record of the intensity of erythemal energy and the E-viton-hours per sq. cm. in the radiant energy received by a horizontal

surface from the sun and entire sky. The data are presented in Figs. 23 and 24 in Chapter II.

The wiring diagram for this integrating meter is illus-

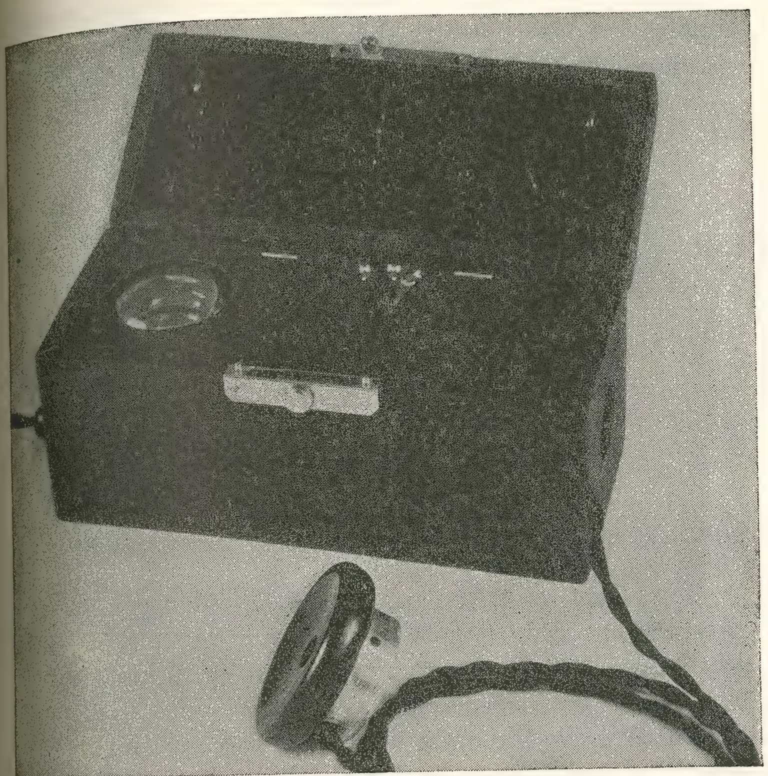


Fig. 134. A pocket-size ultraviolet meter for connection to an ordinary circuit 115-volt alternating current.

trated in Fig. 133, as developed for operation directly on a 115-volt alternating-current supply. The half-wave rectifier tube *1-V* furnishes direct current to the photocell *PC* and for the plate current of a vacuum tube *71-A*. The photocell current charges the condenser *C-2* until its voltage rises high enough to cause a discharge through the 0.25-watt

neon glow-lamp *N*. This produces a momentary negative bias on the grid of the vacuum tube *71-A* and a temporary reduction of its plate current. A telephone-message recorder *MR* in series with the plate of *71-A* registers the impulse and also operates the switch *S-4* which gives a visual indication of the registration.

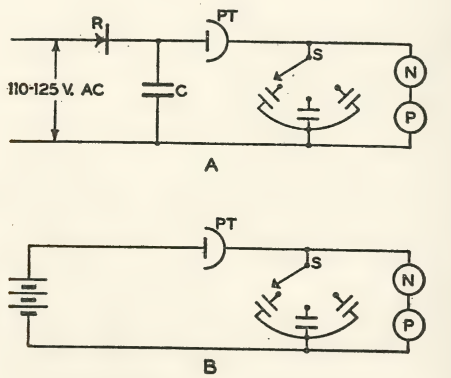


FIG. 135. Wiring diagrams: *a*, for the ultraviolet meter illustrated in Fig. 134; *b*, for battery-operated ultraviolet meter illustrated in Fig. 136.

Simplified portable meters are desirable for many investigations. By eliminating the indicating meters and substituting a telephone receiver, rather small integrating meters have been developed by Taylor[123] which are adequately sensitive for many researches and field investigations.[114] A pocket-size integrating meter is illustrated in Fig. 134. It utilizes a cadmium-alloy phototube *PT* whose location in the circuit is shown in *A*, Fig. 135. A small high-voltage rectifier *R* provides half-wave rectification and charges the condenser *C* to furnish direct current for the phototube. By means of the 3-contact switch *S* the phototube can be connected to any one of three other condensers of different capacities to vary the sensitivity of the meter. The phototube current charges the series condenser

C which in turn discharges through the 0.25-watt neon lamp *N*. A telephone receiver *P* emits an audible click at each discharge. The intensity of ultraviolet energy, or of erythemal flux in the case of natural or artificial sunlight, is proportional to the rate of clicking of the telephone receiver. The total number of clicks in a given period of time is proportional to the total quantity of the ultraviolet or erythemal energy received by the phototube in the given time. The phototube is of the vacuum type and, since the applied voltage is above the value at which the phototube current becomes constant, the meter rate is very little affected by variations in line-voltage. For example, it was found that a 30-percent change in voltage altered the rate of clicking only 4 percent.

In Fig. 136 is illustrated a compact meter operating on the same principle but using dry batteries instead of rectified alternating current. With ordinary usage, the life of the batteries is of the order of their shelf life. This meter is necessarily larger than the one illustrated in Fig. 134 in order to accommodate the batteries but it weighs only 5 pounds. Its wiring diagram is illustrated in *B*, Fig. 135. A meter of this type has been carried far beyond the boundaries of civilization for the purpose of measuring the erythemal energy in daylight in the jungle, in the open and on mountain tops. On the inside covers of these meters, illustrated in Figs. 134 and 136, are tabulated the necessary data for converting the rate of clicking into microwatts or E-vitons per sq. cm. of ultraviolet or erythemal energy, depending upon the source of radiant energy.

In a number of these meters described and used by the author and his colleagues, cadmium-alloy phototubes are employed with amplifiers designed for the particular need. Since they are essentially phototube amplifiers, they may

be used with any type of phototube to measure the intensity of radiant energy to which the particular phototube is

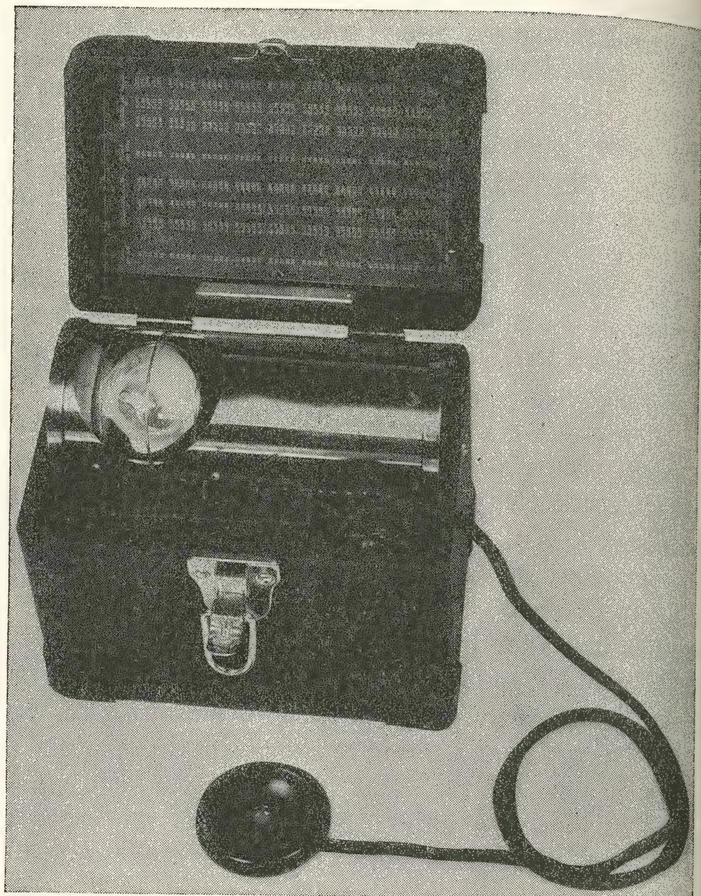


Fig. 136. A battery-operated ultraviolet meter which operates on the same principle as Fig. 134.

sensitive. For example, when used with a caesium phototube the result is a very sensitive meter for light or visible energy and for long-wave ultraviolet energy. By com-

bining a suitable phototube and filter, energy in various spectral ranges can be measured.

The measurement of long-wave or near-ultraviolet energy is of interest in connection with fluorescent materials and effects and in other ways. Some of the devices which have been described in this chapter can be used by

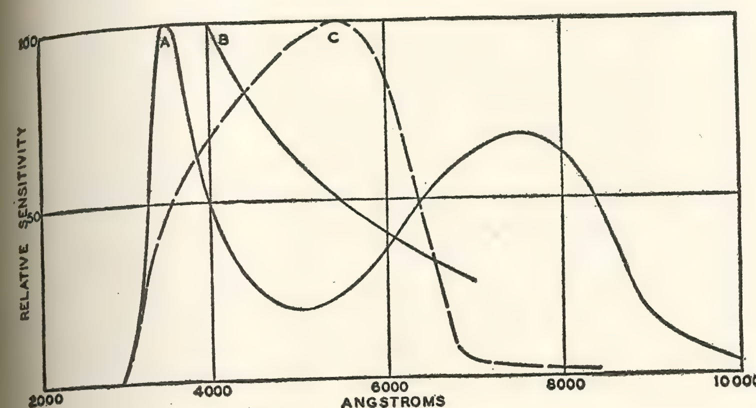


Fig. 137. Spectral sensitivity of *A*, PJ-22 phototube; *B*, FJ-401 phototube; *C*, blocking-layer photo-sensitive cell used in the General Electric Light Meter.

altering the resultant spectral sensitivity of the receiver or by choosing one of the proper spectral characteristics. One of the simplest devices is made by using a "black light" filter with the light meter illustrated in Fig. 122.

It is seen in *C* of Fig. 137 that the blocking-layer light-sensitive cell, used in the light meter, is sensitive to long-wave ultraviolet energy as well as to visible energy. Therefore, with a suitable filter, such as red-purple ultra (Corning 587) about 5 mm. thick, the light meter can be used to measure ultraviolet energy from $\lambda 3200$ to $\lambda 4000$. Most mercury-arcs have a strong emission band at $\lambda 3650$ to $\lambda 3663$. This filter has a transmittance of approximately 65

percent in this spectral region. It absorbs most of the energy from mercury-arcs emitted in the spectral bands of λ4048 and λ4358. The spectral transmission of typical ultra-violet filters is illustrated in Fig. 138. These Corning filters, Nos. 5860, 5874 and 5970, transmit practically no light or visible energy. The other glasses are those used with various

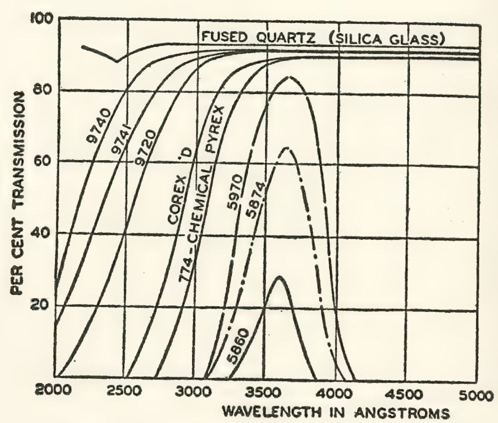


FIG. 138. The spectral transmission of typical ultraviolet-transmitting filters, Corning 5860, 5874, and 5970, which transmit practically no visible energy.

sources of ultraviolet energy. They can be used for phototubes and other receivers.

Ultraviolet energy in the region of λ3650 can also be measured by various phototubes that are now available. The spectral sensitivities of some of these are presented elsewhere [114] and data can generally be obtained from the manufacturer of phototubes, but some examples may be of interest. In *B* of Fig. 137 it is seen that the spectral sensitivity of phototube FJ-401 is quite high in the region of λ3650. With an ultraviolet-transmitting filter such as Corning 587 red-purple ultra, this phototube effectively measures the long-wave ultraviolet energy emitted by certain mercury-arcs and other sources. It is seen that such a phototube as PJ-22 used with proper filters can be used to measure light. In this case the filters should modify the spectral transmission so that it approximates the spectral sensitivity curve of the visual sense as illustrated in Fig. 33.

In many determinations of the spectral distribution of energy in daylight,[99] it was found that when these spectral curves were plotted on an equal-illumination basis, they intersected at approximately the same spectral region. At λ5600, the spread of the various curves is only about 5 percent. Therefore, the intensity of a narrow band in that region is almost directly proportional to the illumination in footcandles. Gibson [124] has described a filter with high transmission at λ5600 and with low transmission for energy shorter than λ5400 and longer than λ5700. This filter could be used with phototube PJ-22 or FJ-401 to measure intensities of daylight.

LARGE-SCALE DAYLIGHT INDICATOR

An instrument was developed primarily as a large-scale indicator of the footcandle-intensities of daylight outdoors.[114] The scale of one of the devices, illustrated in Fig. 139, has been located in the author's office for more than a decade. The arrow indicates at all times the intensity of illumination on a horizontal surface outdoors exposed to the entire sky. It could be installed on a billboard or elsewhere. By using a proper receiver, such as a cadmium-alloy phototube, it would register the intensity of erythemal energy in any unit such as E-vitons per sq. cm. Installed on a bathing beach or near an outdoor swimming pool, it could indicate the number of minutes of exposure necessary to obtain a minimum perceptible erythema or a vivid erythema on average untanned skin.

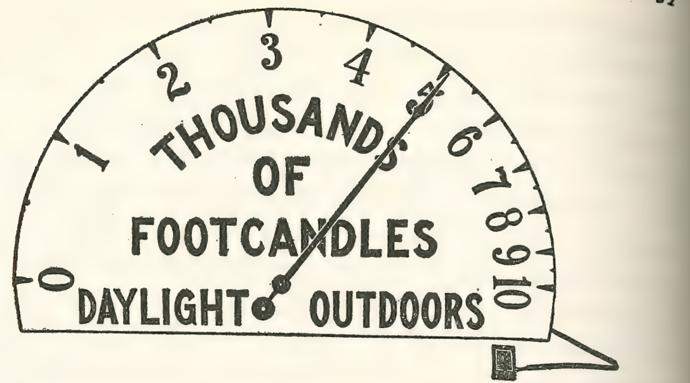


Fig. 139. A large-scale footcandle indicator of outdoor daylight which can be installed indoors or outdoors. It could also indicate intensities of erythemal energy at bathing beaches and outdoor swimming pools.

The diagram of the electrical circuit of an indicator of daylight intensities in footcandles is illustrated in Fig. 140. The meter includes three distinct electrical circuits as follows:

(1) A light-sensitive cell which supplies current to a micro-relay having high- and low-current contacts. Opposing the light cell, across the relay, is a high-resistance potentiometer and battery which automatically tend to keep the micro-relay needle floating between the high- and low-current contacts.

(2) An amplifier circuit employing a rectifier tube (5Z4) and a twin triode tube (6N7). Relays R-1 and R-2 in the two plate circuits control the motion and direction of rotation of

(3) A reversible motor RM which drives the indicating hand and the contactor of the potentiometer.

When the micro-relay needle touches one of the contacts, it short-circuits one of the grids and the cathode, putting zero bias on that grid of the 6N7 tube and producing a large increase in the current in the corresponding plate circuit. This causes relay R-1 or R-2 to close and start the motor rotating in the proper direction to move the potentiometer contact and bring the micro-relay needle back to the floating position. The motor used is a reversible Tele-

chron motor having a speed of 2 rpm, but the relays are capable of controlling a much more powerful motor such as would be required to move a large pointer on a billboard. A 1.5-volt dry cell is used with the potentiometer and,

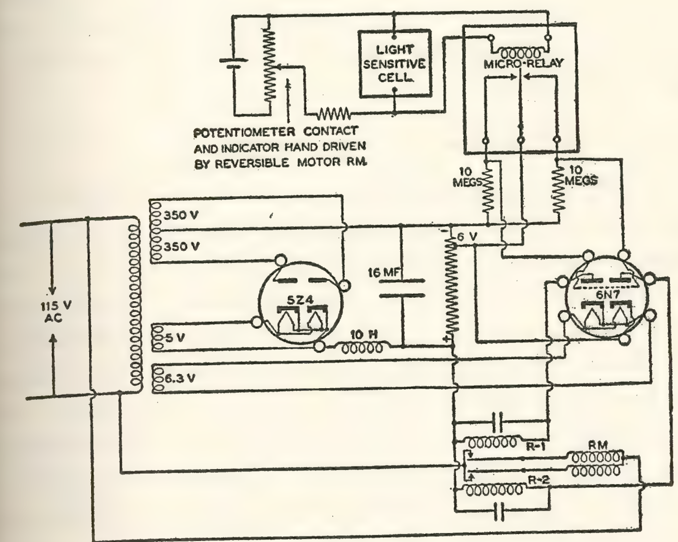


Fig. 140. Diagram of the electrical circuit of a device for indicating outdoor intensities of illumination. By using the proper receiver it can indicate erythemal energy and the time in minutes necessary to obtain any degree of erythema on average untanned skin.

since the current drain is very low, its life is quite long. All other power for the meter is obtained from a 115-volt alternating-current supply.

This indicating instrument has many applications, such as maintaining the constancy of artificial illumination, ultraviolet energy, etc., by using a reversible motor to control resistance in the lamp circuit. It can be employed to measure the ultraviolet energy in daylight by using a phototube of suitable spectral sensitivity. If the current obtainable

from the phototube is too small to actuate the micro-relay directly, it can be amplified before application to the relay.

Inasmuch as the micro-relay may in time fail to operate properly by reason of its contacts sticking together, there has more recently been developed a meter employing no relays. The new meter is applicable principally with phototubes rather than with the blocking-layer type of light-sensitive cell.

TUNGSTEN-FILAMENT DRYING LAMPS

Tungsten-filament lamps, as efficient producers of radiant energy, are becoming widely recognized for drying paints, vegetables, fruits and other materials. In many cases the surface of the material merely absorbs the radiant energy. Then by conduction the material is heated at a depth. The result is a hastening of evaporation of the volatile medium in the paint, water in fruits and vegetables, etc. These lamps afford a safe, convenient and readily controllable means of drying materials. In general the operating temperature of the filament is determined by the economics of the case.

In case a material is appreciably transparent or translucent to radiant energy of a certain spectral range, it is easy to determine the color-temperature of the filament which will produce this radiant energy most efficiently. In some industrial processes it may be worth while to fit the filament temperature to the task.

UNITS, TERMS AND MAGNITUDES

Owing to a lack of standardization it is inevitable that various units and terms are used interchangeably. Therefore, some of their relationships are presented herewith. In addition some relatively new terms used in these chapters are included here. As emphasized in early chapters the

term *radiant energy* is commonly used for *radiant power* but usually this is merely inexact and not confusing. Exposure or dosage is also commonly confused with *intensity* of exposure or dosage.

Energy

1 erg = 1 dyne-cm.
10^7 ergs = 1 joule
= 1 watt-sec.
= 0.239 gram-calorie

Power

1 watt = 10^7 ergs per sec.
= 10^3 milliwatts
= 10^6 microwatts
1 erg per sec. = 10^{-7} watts
= 10^{-4} milliwatts
= 10^{-1} microwatts
1 E-viton = 10 microwatts of erythemal flux

Intensity of radiant power (per unit area)

1 microwatt per sq. cm. = 10 ergs per sq. cm. per sec.
= 0.929 milliwatt per sq. ft.
1 milliwatt per sq. ft. = 1000 microwatts per sq. ft.
= 1.076 microwatts per sq. cm.

Intensity of radiant power (per unit solid angle)

The surface of a sphere subtends 4π steradians.
1 milliwatt per steradian produces 0.1 microwatt per sq. cm. on a spherical surface at one meter from a point source.

Exposure or dosage

This is the product of radiant power and duration in seconds, minutes or hours.
1 microwatt-second = 10 ergs
1 microwatt-minute = 600 ergs
1 E-viton-min. = 6000 ergs of erythemal flux

Intensity of exposure or dosage (per unit area)

1 microwatt-second per sq. cm. = 10 ergs per sq. cm.
1 microwatt-minute per sq. cm. = 600 ergs per sq. cm.
1 E-viton-minute per sq. cm. = 1 Finsen-minute

Various Applications of Radiant Energy

THE PRIMARY purpose of this book is to provide a scientific basis and technology for certain major uses and effects of ultraviolet energy. With the availability of various efficient sources of germicidal and biologically-beneficial energy, extensive applications in the indoor world are now possible. Besides these major uses and effects there are countless special applications of radiant energy from the various sources available. All these will eventually be made by those who are intimately associated with the needs. It is only necessary to become acquainted with the variety of artificial sources and the means of applying them to their needs. The preceding chapters should provide helpful data for many of these specific applications. However, additional aid may arise from brief discussions of some specific uses which promise to become extensive.

STERILIZING HIGHLY ABSORBING MATERIALS

Germicidal energy of λ2537 must reach micro-organisms in sufficient intensity for a sufficient period of time if it is to kill them. Fortunately, air is quite transparent to this energy and the absorption-coefficients of clear water are not too great; but most other materials are highly absorbing. As indicated in Table XLVII rather thin layers of beer, wine and vinegar absorb 90 percent of the incident germicidal energy. However, such liquids can be disinfected to a high degree by this energy if they are irradiated in thin layers. This germicidal energy is rather vicious and it may adversely affect a material. Obviously, this must be determined before proceeding further.

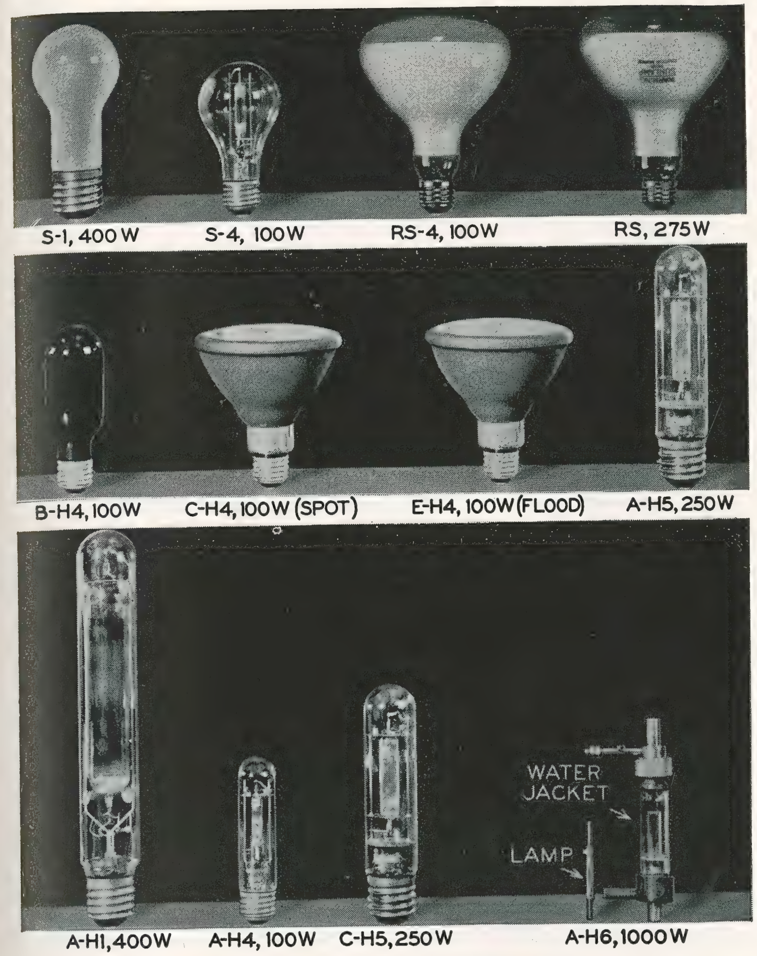


PLATE XVI. Various efficient sources of light and ultraviolet energy for various purposes.

In Fig. 141 are illustrated two vertical sectional views of a suitable metal container for irradiating highly absorbing liquids. In the cross-section *A* the germicidal sources *G* are seen to be installed close to a thin layer *L* of the flowing liquid. The corrugated bottom is indicated as one means of stirring or turning over the liquid. The cross-section *B* indicates the long tubular germicidal sources. Doubtless the

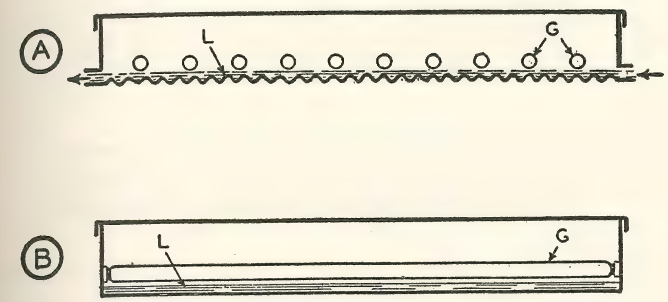


Fig. 141. Highly absorbing liquids can be treated in thin layers with germicidal sources *G*. The liquid may flow in a thin layer *L* at the proper rate for adequate disinfection.

ends and the sockets should be covered with rubber sleeves. The rate of flow is determined by the results obtained. Where plenty of time is available, it is possible that beer, wine, vinegar and other liquids might be adequately sterilized. The practicability and economics are factors that can readily be determined for any specific case.

In the disinfection of water it is generally less practicable and efficient to immerse the germicidal sources. However, it is justifiable to immerse them in highly absorbing liquids as indicated in Fig. 142. In the cross-section *A* two different groupings of germicidal sources *G* are shown in *C* and *D*. The liquid *L* enters through *I* and after meandering it flows out at *O* at an appropriate rate, depending upon its absorption-coefficient and the kind of

micro-organisms to be killed. Inasmuch as the liquid is not under pressure, it appears practicable to use rubber sleeves *S* as shown in the cross-section *B*. Although each germicidal source is of low wattage, many of them will represent a total wattage that may be rather high. Obviously, the heating effect upon the liquid must be taken into account.

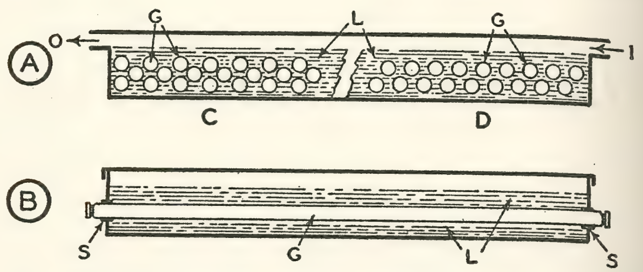


Fig. 142. Germicidal sources may be immersed in highly absorbing liquids.

Milk in a very thin layer is highly absorbing. Nevertheless, many years ago experiments were made with quartz mercury-arcs in disinfecting very thin films. In one case this film was gathered on the edge of a revolving disk and was wiped off and collected after exposure to the ultraviolet energy. Inasmuch as a 30-watt germicidal source is nearly as effective in killing micro-organisms as a 300-watt quartz mercury-arc, it is possible that milk might be successfully treated in a device such as that illustrated in Fig. 142. Ozone imparts an undesirable taste to milk. Therefore, the air in the milk or in contact with it might have to be eliminated or at least reduced.

The same principles apply to the disinfection of thin layers of solid materials such as paraffin. The rate at which the material passes during processing determines the number of germicidal sources which are placed close to the

material. These factors determine the exposure measured in intensity and time.

Inasmuch as the absorption-coefficient is so important in determining the design or practicability of a germicidal installation, Table XLVIII is presented. The data apply

TABLE XLVIII

Percentages of Incident Energy of λ2537 Absorbed by Different Depths of Non-Turbid Homogeneous Media

Absorption Coefficient a *(per Inch)*	*Depth in Inches* 0.1	0.2	0.5	1.0	2.0	5.0	10	20	50	100
.01	0.1	0.2	0.5	1.0	2.0	5.0	9.0	18	40	60
.02	0.2	0.4	1.0	2.0	4.0	9.0	18	33	60	85
.05	0.5	1.0	2.5	5.0	10	22	40	60	90	98
.10	1.0	2.0	5.0	9.8	18	38	60	86	98	
.20	2.0	4.0	9.0	18	32	60	85	98		
.50	4.8	9.0	22	38	60	91	98			
1.0	9.0	18	38	60	85	98				
2.0	18	32	60	85	98					
5.0	37	60	90	98						
10	60	85	98							
20	85	98								
50	98									

$$P = 100(1 - e^{-ad})$$

P = Percentage of energy absorbed
a = Absorption-coefficient
d = Depth of absorbing medium

only to non-turbid homogeneous media. The percentages of the incident germicidal energy that are absorbed by layers varying in depth from 0.1 in. to 100 in. are indicated for various absorption-coefficients, *a* per inch. Emphasis is given to the lesser depths of the absorbing medium. The data were computed according to the exponential law for clear or non-turbid homogeneous media.

DISINFECTING AIR FOR INDUSTRIAL PROCESSES

In many industrial processes it is desirable and practicable to disinfect the air so as to prevent contamination

of products. In some cases it may be desirable to irradiate the upper stratum of air in the entire room and to supplement this with localized germicidal energy over certain processing areas. In others it appears more practicable to provide rather complete insurance against contamination from air-borne micro-organisms by enclosing a process or production line.

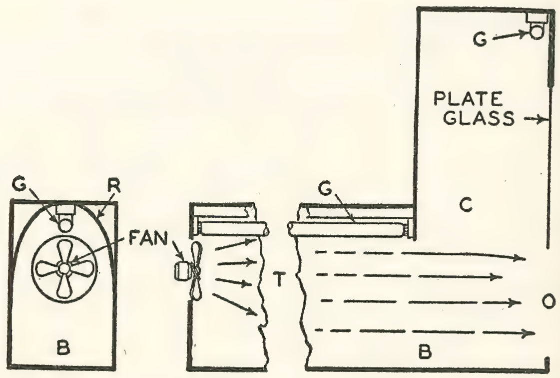


FIG. 143. An arrangement for disinfecting air in a tunnel T for various purposes. In this case the worker projects his protected hand in O and packs sterile materials in disinfected air.

As illustrated in Fig. 143, a tunnel T can be short or long, depending upon the requirements. Germicidal sources G are installed in aluminum reflectors R. In one successful operation sterile jars proceed along a moving belt B toward the compartment C. A worker is located at the right-hand end looking through the plate-glass window. With his protected hands and arms projecting through the opening O, the worker fills the sterile containers with the sterile product. A small fan, operating at low speed, gently pushes the air from left to right through the tunnel T and out at O. Thus the air can be disinfected to any degree depending upon the length of T and the wattage of G. The compartment C contains a germicidal source G installed as shown.

The eyes of the worker are protected by the ordinary plate glass. Many variations of this principle can be made to suit various packing and other procedures.

In many industrial processes contamination can be reduced or completely prevented by enclosing larger areas and volumes. The prevention of spoilage by air-borne organisms is practicable and many recommendations of this sort have been made. Fig. 143 illustrates an actual installation of germicidal sources which have prevented spoilage of products or have improved their acceptability.

Germicidal energy is used to a considerable extent where meat is stored above the freezing temperature. There is little doubt that this refinement in processing and storing products will find wide acceptance.

Many products cannot be completely sterilized by germicidal energy for they are opaque to this energy. Their surfaces can be treated successfully in many cases. However, many products are rendered sterile by heat in the processing and they can be protected from contamination by air-borne organisms.

STERILE STORAGE

There appear to be extensive fields for germicidal energy for rendering air sterile for the storage of sterilized materials. In Fig. 144 a vertical cross-section of a cabinet is illustrated. This was made for preventing contamination of bacteriological supplies and equipment by air-borne microorganisms. The sterilized petri dishes and other materials rest on the bottom of the cabinet. A germicidal source is located at the coincident foci of two aluminum parabolic reflectors. These provide a cross-fire of germicidal rays. The front can be closed and the confined air can be disinfected to a high degree.

Cabinets for sterile storage can be simpler than that illustrated in Fig. 144. A germicidal source can be located horizontally on the inside above the door of the cabinet. If the cabinet has horizontal shelves, a germicidal source may be installed vertically inside at one side of the door or one at each side of the door. There are countless uses and

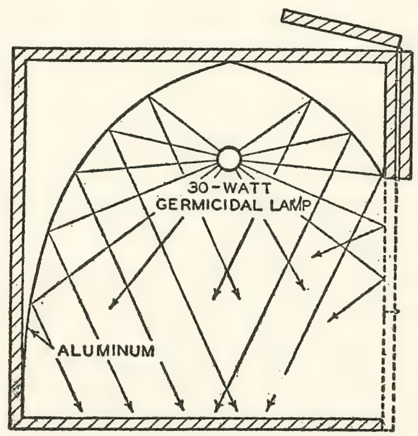


Fig. 144. A cabinet for sterile storage of materials. Many simpler designs are practicable.

places for such cabinets. They are not intended for sterilizing the materials, but for maintaining a sterile environment for storage. In the home babies' equipment and materials can be stored in a small cabinet in which an 8-watt or even a 4-watt germicidal source is sufficient. Such cabinets will serve well in hospitals, dispensaries, surgeries, dental offices, barber shops, etc.

In the storage of furs, for example, germicidal energy acting for a long time might damage the materials. In such cases the air might be sterilized in a small compartment through which it is circulated and from which it is discharged into the storage space.

EXTENSIVE USES OF FLUORESCENCE

Not many years ago the production and use of fluorescence were relatively rare and not of much practical importance. If one wished to utilize this phenomenon for an interesting effect or a utilitarian purpose he had to make his own fluorescent materials and adapt a make-shift filter to a source of ultraviolet energy. With the advent of various sources of long-wave ultraviolet energy, many excellent fluorescent materials have become available. However, neither the sources nor the materials would be of much general use if appropriate filters were not available. Fortunately, heat-resisting glass filters are available which transmit long-wave ultraviolet energy in the region of $\lambda 3600$ without transmitting appreciable visible energy. The spectral transmissions of three of these glass filters are illustrated in Fig. 138.

As a result of the availability of socalled "black light" a great expansion of the use of fluorescence has taken place. Many variations are possible in theatrical or spectacular fields. However, the strictly utilitarian uses are even more varied and numerous. The applications in warfare included fluorescent maps, scales on instruments and signaling. Invisible markings on laundry and other materials are practicable. These ultraviolet sources are standard equipment in crime detection. Fluorescing patterns in the carpeting of the aisles of motion-picture theatres are suggestive of the many uses of fluorescence as a safety aid. Countless novelties can utilize fluorescent materials and "black light" and many of these combine interest with utilitarian value.

An enormous number of common materials are excited to fluorescence, and in the absence of light there are many uses of this phenomenon. For example, many minerals fluoresce a distinctive color so that black light is an aid in

prospecting and mining. Unfortunately, fluorescence and phosphorescence are also due to minute "impurities" so that the color of the phosphorescence or fluorescence of a mineral is not an infallible guide. Nevertheless, a source of black light provides a person with something equivalent to another visual sense, which is helpful in many ways.

These are mere glimpses of the phenomenon and its utilitarian, artistic and novel possibilities. Although any source of ultraviolet energy may be equipped with a filter, some of the major sources available are illustrated in Plate XVI. Obviously the sunlamps, S-1, S-4, RS-4 and RS emit long-wave ultraviolet energy and can be effectively used. However, the middle group in Plate XVI is generally used. The B-H4 is a 100-watt mercury lamp with an outer bulb which is the red-purple filter. The other mercury lamps must have accessory filters. The C-H4 has a concentrating reflector and the E-H4 has a less concentrating one.

Fluorescent lamps for general lighting purposes have the inside of their glass tubes coated with socalled phosphors which emit light or visible energy on being excited by the ultraviolet energy of λ2537 emitted by the low-pressure mercury vapor. Instead of using these phosphors, a material is used which emits long-wave ultraviolet energy when excited by the energy of λ2537. This results in the type 360 BL fluorescent lamp. Obviously, the principle can be applied to fluorescent lamps of any wattage. A spectrogram of the energy radiated by this type of fluorescent lamp is included in Plate I. This source must be used with a filter such as 597.

All tungsten-filament lamps emit some long-wave ultraviolet energy. Therefore, when they are equipped with a proper filter they are useful where relatively low intensities of this exciting energy are adequate.

There should be a term analogous to the lumen and E-viton for expressing the output of long-wave ultraviolet energy according to its ability to excite fluorescence. However, fluorescent materials vary widely in their response to ultraviolet energy of various wavelengths. Therefore, a standard one would have to be selected, but this would not be representative of most of the other materials. Possibly the output of radiant energy between λ3500 and λ3700, measured in units already available, would be the best solution at the present time. This wavelength range includes the maximal spectral transmission of the red-purple ultra filters in common use. Measurements of the total ultraviolet energy passing through a standardized red-purple filter are quite helpful. The author has standardized such a filter for use with the General Electric Light Meter and has found that the measurements are very useful. In this way it is possible to rate different sources of socalled black light. This matter is discussed in Chapter XV.

EFFICIENT BATH CABINETS

For many years the author has wondered why socalled light-baths have not been more widely used. When one notes the popularity of Turkish baths with their hot dry and humid rooms he naturally wonders why cabinets containing high-efficiency tungsten-filament lamps have not been developed for widespread use even in homes. Naturally, a place must be found for them, but if they are collapsible as illustrated in Fig. 145, and properly finished they can be placed in a bedroom, bathroom, closet or any convenient place. However, if bathrooms were viewed as they should be they might be termed health-rooms. They might well be equipped with a socalled light-bath, either portable or permanently installed.

In Chapter XIII it is seen that the ideal source for heating bodily tissue to a depth is one which efficiently produces long-wave visible energy and short-wave infrared energy. Bodily tissue is composed largely of water and, therefore, its spectral transmission is largely determined by that of water. This fact is illustrated in Figs. 109 to 112.

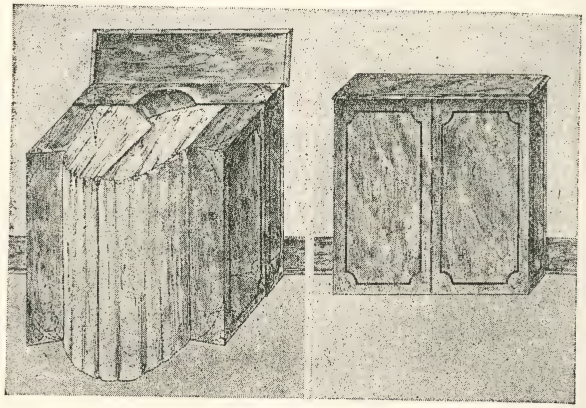


FIG. 145. An example of a collapsible cabinet containing high-wattage tungsten-filament lamps for heating bodily tissue at a depth. With special bulbs moderate intensities of erythemal energy are available.

The author [100] published data of this sort many years ago [102] but notwithstanding the undeniable proof that tungsten-filament lamps of high wattage are the best artificial sources for such use, carbon-filament lamps have continued in use. Even non-luminous heaters are still sold for this purpose. Some manufacturers of bath-cabinets did change from carbon-filament lamps to tungsten-filament lamps of the lesser wattages. However, 300-watt tungsten lamps are much more efficient for bath-cabinets than 40-watt tungsten lamps of the same total wattage. For these reasons a bath-cabinet containing 300- and 500-watt tungsten lamps was extensively studied by Luckiesh and Holladay.

A high-wattage tungsten lamp was installed in each of the 8 inside corners of a cubical cabinet. The total wattages studied varied from 900 to 4000 watts and the average intensities of illumination over an average of 19 sq. ft. of the naked adult subjects varied from 400 to 1800 foot-candles. The duration of exposure varied from 7 to 60 minutes during which respiration, blood pressure, bodily temperature and heart-rate were recorded. From these experiments it was concluded that a 300-watt lamp in each of the 8 corners was more than adequate. In fact, it was concluded that the adult, being in a sitting position, would prefer to have the lamps in the two corners near the feet eliminated. This leaves six 300-watt lamps, and the total of 1800 watts was found to be adequate.

In this cabinet an adult is quite comfortable notwithstanding the fact that his mouth temperature might rise 1 or 2 deg. C. in ten minutes and he might lose nearly two pounds in weight. As explained in Chapter XIII, the radiant energy from $\lambda 6000$ to $\lambda 14{,}000$ penetrates by transmission, not by conduction as from a hot towel. The energy that heats the surface of the skin is partially conducted, but it is also exciting the network of sensory nerves. One can readily note the difference in "skin comfort" between equal wattages of 300-watt tungsten lamps and of 40-watt tungsten lamps or of carbon-filament lamps. The benefits are the same as those in hot dry or humid Turkish baths. The profuse perspiration keeps the skin moist and cleanses the pores. For normal healthy persons who lead a more or less sedentary life there is little doubt that the stimulation of the circulatory processes is beneficial. Incidentally, the respiration and pulse-rates generally rise appreciably during a 10-minute exposure in the cabinet.

There is no conclusive evidence that the visible or infrared energy in itself is beneficial in the sense that ery-

themal energy is beneficial by the production of Vitamin D and possibly in other ways. However, it is likely that all is not known about the effects of radiant energy in sunlight. At least it was an environmental factor for eons and possibly is of some direct value when the skin is exposed to it.

When the entire body, with the exception of the head and neck, is exposed a large area of the skin is the receiver. In Chapter X it is seen that suberythemal dosages of ultraviolet energy prevented and cured rickets when only a small fraction of the skin of an infant was exposed. It appears probable that even smaller dosages are necessary when the entire body is exposed to erythemal energy. At any rate, when 300-watt tungsten-filament lamps with special ultraviolet-transmitting glass were used in the bath-cabinet, a dosage equivalent to about 0.1 MPE was obtained in 10 minutes over the entire area of skin. This might be an adequate biologically-beneficial dosage.

The comfort and convenience in using such a bath-cabinet is far greater than is experienced in hot dry or humid rooms. Furthermore, such bath-cabinets are readily installed. It appears to the author that this will eventually be a major use of radiant energy. Combining erythemal energy with the penetrating visible and short-wave infrared energy makes it doubly attractive.

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Applications of
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D. VAN NOSTRAND
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READING AS A VISUAL TASK

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From the two viewpoints of visibility and readability, this book gives a detailed account of the most important and most common of all critical visual tasks — reading. Every aspect of this subject is fully explained, including the effects of type-size, type-design, leading, line length, level of illumination, paper and ink, printing and various methods of reproduction. This is the first comprehensive treatment by means of new devices, techniques and criteria which the authors have evolved from their intensive researches in this immediate field, which have extended over a period of more than ten years.